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PILOT BACKGROUND AND VEHICLE PARAMETERS GOVERNING CONTROL TECHNIQUE IN STOL APPROACH SITUATIONS

SAMUEL J. CRAIG IRVING L. ASHKENAS
ROBERT K. HEFFLEY

SYSTEMS TECHNOLOGY, INC.
13766 SOUTH HAWTHORNE BOULEVARD
HAWTHORNE, CALIFORNIA 90250

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Samuel J. Craig, Irving L. Ashkenas, Robert K. Heffley

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16. Abstract

This report describes the results of a simulator investigation to identify path control restrictions for STOL aircraft which are independent of short period attitude control qualities. Various aspects of path response coupling were explored using selected variations in thrust inclination and X_w, the incremental drag with angle of attack. Piloting technique was another variable induced through a pertinent set of instructions and briefings. It was found that the pilot's opinion of a given situation and control technique depends on the details of the response coupling involved; and on the pilot's background-related bias for a "preferred" technique.

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SECTION I

INTRODUCTION

This report presents and analyzes the results of a specially designed experiment conducted at Ames Research Center in connection with the program documented in Ref. 1, part of a continuing series concerned with potential flight handling criteria for STOL transport aircraft. The overall objective of the experiment was to explore and identify certain basic problems pertinent to manual approach path control of STOL aircraft. These problems are characterized by the nature of the relative airspeed (u) and climb ($\dot{h}$) responses to the pertinent pilot inputs. The most desirable situation from the standpoint of ease of control is one which produces pure u in response to one control input (e.g., δ_e) and pure $\dot{h}$ in response to another control input (e.g., δ_T). Unfortunately, such purity is seldom inherent in even conventional aircraft, especially when approaching at speeds below that for minimum drag (i.e., so-called "backside" operation). For powered-lift STOL aircraft the inherent impurities are even more pronounced due to normally prevalent coupling effects (e.g., thrust inclination and offset, high α-induced drag, etc.). Such "contamination" of the desired pure responses can sometimes be alleviated by a change in control technique, i.e., by using an alternative set of inputs for the primary control of u and $\dot{h}$. The extent to which any control technique is acceptable depends then on whether the resulting u and $\dot{h}$ responses are thereby purified; or, if still contaminated, whether they can be separated by the pilot because of their different frequency (or response-time) content.

Viewed in this light, the problems of STOL path control boil down to questions concerning the allowable (limit) coupling characteristics of "secondary" and primary motions. However, since the degree of coupling encountered is in general a function of the piloting technique employed, there are further questions as to the dependence of technique on coupling and allowable coupling on technique.* Both sets of questions have been previously addressed in past experimental and analytical efforts indirectly applicable to STOL aircraft (e.g., Refs. 4, 5, and 6). However, most such data and their analyses suffer from yet other contaminations which becloud the issue of acceptable coupling. Such contamination can occur because of inadequate or different primary responses, poorly matched control sensitivity, insufficient control power, or interfering (and poor) short-period characteristics.

In the work reported here such extraneous effects were eliminated by careful experimental design directed at the following simple detailed objectives:

1. To determine the key parameters governing path control independent of attitude regulation requirements.

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*Piloting "technique" is not to be confused with "skill." In our context, technique relates to the sensible loop structure utilized, as discussed later.

2. To show how the pilot's selection of an approach control technique is affected by the coupling due to the basic aerodynamic terms X_w and Z_u and due to the effective thrust inclination.

3. To evaluate the hypothesis that the pilot's ability to separate speed and flight path responses governs the control technique utilized and the pilot's handling quality opinion.

In Section II, which follows, we discuss the theoretical aspects of coupling/pilot-technique problems and use these as the bases for the Section III description of the experimental design and test procedures. Section IV presents and discusses the results in the light of the practical (and theoretical) manifestations of coupling; and Section V presents and summarizes our conclusions Additional auxiliary information, referenced in various portions of the text, is contained in the Appendices.

SECTION II

THEORETICAL CONSIDERATIONS

The basic theoretical aspects of manual path control may be evolved from an examination of the two prevalent piloting techniques, as represented schematically by the block diagrams of Fig. 1. For either technique the inner, attitude loop is fundamental; however the specific requirements on the "tightness" or other qualities of this loop are expected to vary with the outer-loop control technique employed. For example, for "conventional" (CTOL) control of $\dot{h}$ with attitude the closed inner loop bandwidth (a measure of closed-loop response time) must be sufficiently high to permit fairly rapid corrections in $\dot{h}$. By way of contrast, for "unconventional" (STOL) control of $\dot{h}$ with thrust and u control with θ, the normally-expected, and encountered, low frequency u deviations theoretically permit some relaxation of the inner-loop bandwidth. For this technique the primary requirement on the θ loop is to provide phugoid damping and counter thrust (or gust) induced moments.

To eliminate this possible source of difference between the two techniques and concentrate, rather, on outer-loop path (u, $\dot{h}$) control problems arising from various degrees of coupled u and $\dot{h}$ motions, we "normalized" attitude control aspects by utilizing a high gain, rate-command, attitude-hold control system (see Appendix A for details). The attitude response and sensitivity to stick inputs were experimentally tuned to the pilot's desires and a pulse-like stick input was required to obtain an attitude change, as with conventional short-period dynamics; however attitude regulation was maintained automatically.

Under these conditions of constrained attitude, the pertinent dynamics of the aircraft's motions are given by the attitude numerator, i.e., the closed, inner-loop denominator, Δ', given in general by

$$\Delta' = \Delta + G_\theta N^{\theta}_{\delta_e}$$

approaches $N^{\theta}_{\delta_e}$ for the large G_θ (in the frequency region of interest) implicit in attitude stabilization. Similar effects occur for the usual control transfer function numerators. The net result, also true (but less consistently so) for "tight" manual control of attitude, is that the pertinent path control transfer functions are given rather simply in terms of the following forms and factors (for $\gamma_0 = 0$*):

*The $\gamma_0 = 0$ initial condition does not detract from the general applicability of these small perturbation relations. Basically the $\dot{h}$ responses so computed are equivalent to deviations normal to the flight path stability axis for the usually small values of γ_0 pertinent to approach conditions.

Characteristic

$$\Delta = N^{\theta}_{\delta_e} = M_{\delta_e}[s^2 + (-Z_w - X_u)s + (Z_wX_u - X_wZ_u)]$$

$$= M_{\delta_e}[s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2] \quad , \quad \text{or} \tag{1a}$$

$$M_{\delta_e}(s + 1/T_{\theta_1})(s + 1/T_{\theta_2})$$

The latter form results if X_w is small or in general if $|X_wZ_u| \ll |Z_wX_u|$, then

$$\Delta \doteq M_{\delta_e}(s - X_u)(s - Z_w) \tag{1b}$$

with $1/T_{\theta_1} \doteq -X_u$ and $1/T_{\theta_2} = -Z_w$

Elevator Responses — assuming $X_{\delta_e} = Z_{\delta_e} = 0$ — are correspondingly given by:

$$\frac{u}{\delta_e} = \frac{-M_{\delta_e}}{\Delta}(X_\alpha - g)\left(s + \frac{gZ_w}{X_\alpha - g}\right) = \frac{-M_{\delta_e}}{\Delta}(X_\alpha - g)(s + 1/T_{u_1}) \tag{2}$$

where $1/T_{u_1} = gZ_w/(X_\alpha - g)$.

$$\frac{\dot{h}}{\delta_e} = \frac{M_{\delta_e}Z_\alpha}{\Delta}\left[s - X_u + \frac{Z_u}{Z_w}(X_w - g/U_o)\right] = \frac{M_{\delta_e}Z_\alpha}{\Delta}(s + 1/T_{h_1}) \tag{3}$$

where $1/T_{h_1} = [-X_u + (Z_u/Z_w)(X_w - g/U_o)]$ (backside term).

Throttle Responses with $M_{\delta_T} = 0$ become

$$\frac{u}{\delta_T} = \frac{M_{\delta_e}X_{\delta_T}}{\Delta}[s - Z_w + X_w(Z_{\delta_T}/X_{\delta_T})] = \frac{M_{\delta_e}X_{\delta_T}}{\Delta}(s + 1/T_{u_\theta})^* \tag{4}$$

where $1/T_{u_\theta} = -Z_w + X_w(X_{\delta_T}/Z_{\delta_T})$.

$$\frac{\dot{h}}{\delta_T} = -\frac{M_{\delta_e}Z_{\delta_T}}{\Delta}[s - X_u + Z_u(X_{\delta_T}/Z_{\delta_T})] = -\frac{M_{\delta_e}Z_{\delta_T}}{\Delta}(s + 1/T_{h_\theta})^* \tag{5}$$

where $1/T_{h_\theta} = -X_u + Z_u(X_{\delta_T}/Z_{\delta_T})$.

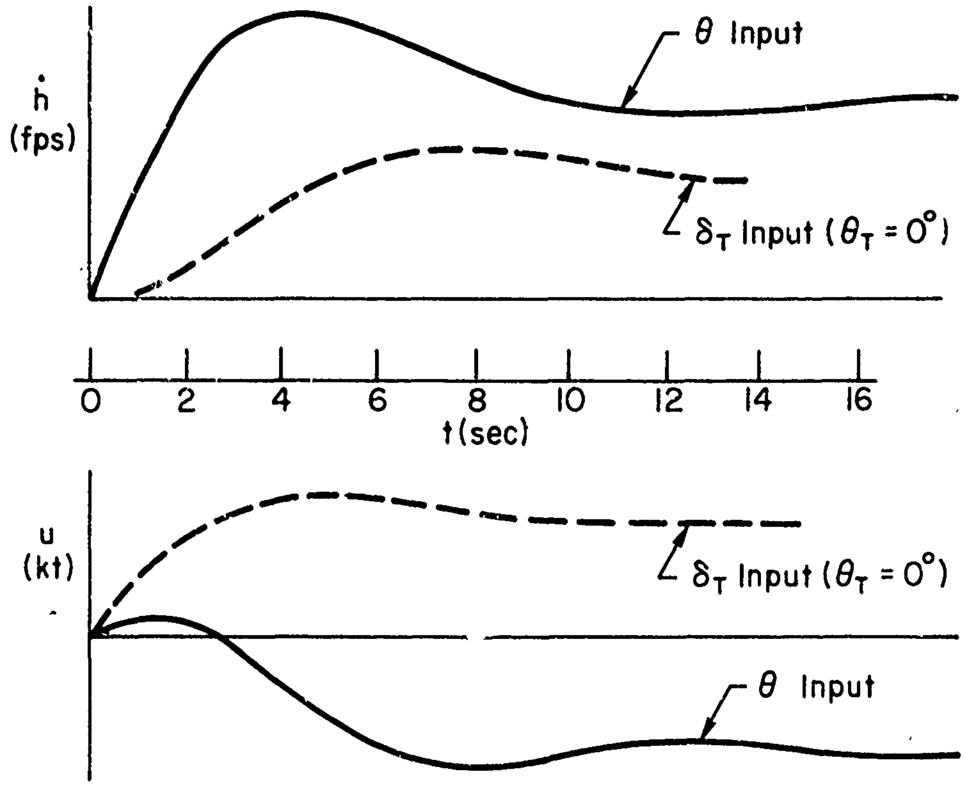
---

*Because of the constrained attitude effect, the u and $\dot{h}$ throttle-response numerators are not the usual simple δ_T numerators, but rather the coupling numerators which apply when two (or more) control inputs are involved; hence the modified notation which reflects conventional multiloop practice (Ref. 17).

Notice from the above relationships that the characteristic ($N^{\theta}_{\delta_e}$) path mode roots for the closed-loop attitude situation are defined by the basic aircraft lift and drag terms, Z_w and X_u; plus the coupling terms X_w and Z_u. The latter derivatives are responsible for the degree of coupling existing between the speed and flight path modes, since they define the corrupting force produced by the desired motion in either the vertical or axial direction. That is, the drag change with vertical motion, X_w, establishes how speed will vary when the aircraft changes flight path or rate of climb (i.e., w) and vice versa for the Z_u term. When the product of these two terms is large and negative the path mode is oscillatory (ω_{θ}); when the product is small the path modes are two first-order subsidences ($1/T_{\theta_1}$, $1/T_{\theta_2}$). Because the control-input transfer function numerators (Eqs. 2-5) are all first order, there can be no true cancellation of (selective) poles and zeros when the path mode is oscillatory. The result is that u and $\dot{h}$ motions then occur with the <u>same</u> dynamics and are therefore <u>inherently</u> coupled. However the relative magnitudes of u and $\dot{h}$ are also important and these are governed, for the throttle inputs, by the ratio $X_{\delta_T}/Z_{\delta_T}$.

The consequences of coupled u and $\dot{h}$ responses are best illustrated by visualizing the control actions and responses associated with the two piloting techniques for a level of $X_w Z_u$ coupling which produces an oscillatory characteristic (ω_{θ}). Considering, the CTOL technique, $\dot{h} \rightarrow \theta(\delta_s)$* and $u \rightarrow \delta_T$, the time-history sketch overleaf shows that for a near step attitude input the $\dot{h}$ response is more rapid and proportionately much greater than the corresponding u response (both $\dot{h}$ and u are sketched to the same scale). In fact, there is essentially no u response in the first three to four seconds, implying a very speed stable situation (due to the positive X_w required to produce the coupled, ω_{θ}, conditions). The final value of the speed change is conventional in that there is a reasonably small reduction for a nose-up attitude. Thus, from the standpoint of flight path control $\dot{h} \rightarrow \theta(\delta_s)$ appears direct and adequate. That is, u responses are decoupled from $\dot{h}$ responses, despite their oscillatory similarity because of magnitude differences. Accordingly, provided speed error remains acceptably small, there are no anticipated $\dot{h}$ control problems. However, it is apparent that, because of its delayed response characteristics, precise u control with attitude (e.g., to correct for winds) would be difficult; furthermore, such corrections will introduce large flight path errors. Turning therefore to speed control with throttle, we see that except for the short delay in $\dot{h}$ response the the $\dot{h}$ and u traces are very similar. That is, there is essentially no way of making a throttle-controlled speed correction without introducing

*This notation is used, for rigor, to denote that θ, as controlled by the stick through the attitude command and stabilization system, is the controlling input in accordance with the block diagrams of Fig. 1. The transfer functions $h/\theta(\delta_s)$ and h/δ_e (attitude constrained) are identical by definition, except for a sign change.



Sketch of Speed and Altitude Rate Response
to Step Attitudes and Throttle Inputs

altitude rate errors of equal magnitude. Physically, this interaction or coupling between u ahd $\dot{h}$ is obvious since with the thrust aligned along the stability axis (θ_T = 0 deg) an h change is produced by a normal force change due to $Z_u u$ (i.e., $\dot{h} = Z_u u$).

Changing techniques, i.e., controlling $\dot{h}$ with throttle and u with θ, only makes the situation more difficult because of the very poor u and associated large, "secondary" $\dot{h}$, response to θ. The pilot effectively has no direct measure of speed regulation for either technique.

At the other extreme, and to illustrate the direct use of the pertinent transfer functions, consider the inherently "decoupled" path mode condition ($1/T_{\theta_1}$, $1/T_{\theta_2}$). The purity of the individual transient response to throttle inputs is governed additionally by the values of $1/T_{u_\theta}$ and $1/T_{h_\theta}$. These zeros are affected by the inherent coupling derivatives, X_w and Z_u, and also by the ratio of the control force derivatives as shown specifically by Eqs. 4 and 5. Without the corrupting effect of these coupling terms on the dynamics (i.e., for

$X_w = X_{\delta_T}/Z_{\delta_T} = 0$), the $\dot{h}$ path response to a throttle input, as previously given (Eqs. 1, 4), is:

$$\frac{\dot{h}}{\delta_T} = \frac{-Z_{\delta_T}(s + 1/T_{h_\theta})}{(s + 1/T_{\theta_1})(s + 1/T_{\theta_2})}$$

where, now,

$$1/T_{h_\theta} = -X_u \doteq 1/T_{\theta_1}$$

thus

$$\frac{\dot{h}}{\delta_T} = \frac{-Z_{\delta_T}}{s + 1/T_{\theta_2}} \tag{6}$$

The corresponding u/δ_T is, of course, identically zero, because X_{δ_T} is zero; however, for finite (but small) X_{δ_T}, $u/\delta_T \doteq X_{\delta_T}/(s + 1/T_{\theta_1})$. The point is both responses are of different magnitude and frequency content, and this desirable feature of uncoupled path modes depends strongly on near-cancellation of certain numerator and denominator factors. Without such near-cancellation inherent decoupling, as defined by well separated values of $1/T_{\theta_1}$ and $1/T_{\theta_2}$, may be only a promise and not a reality.

Similar but incomplete pole-zero cancellation and resultant separation of u, and $\dot{h}$, responses occurs for stick inputs and the above-postulated conditions; i.e., for $X_w = 0$, $1/T_{u_1} = -Z_w = 1/T_{\theta_2}$, and

$$\frac{u}{\theta(\delta_s)} \equiv \frac{-u}{\delta_e} = \frac{X_\alpha - g}{s + 1/T_{\theta_1}}$$

$$\frac{\dot{h}}{\theta(\delta_s)} \equiv \frac{-\dot{h}}{\delta_e} = \frac{-Z_\alpha(s + 1/T_{h_1})}{(s + 1/T_{\theta_1})(s + 1/T_{\theta_2})} \tag{7}$$

where

$$1/T_{h_1} = -X_u - (g/U_o)(Z_u/Z_w) = 1/T_{\theta_1} - (g/U_o)(Z_u/Z_w)$$

Although the u response is "pure" and slowly subsident ($1/T_{\theta_1}$) the $\dot{h}$ response while basically fast ($1/T_{\theta_2}$) can also exhibit the same slow subsidence. Whether it does so depends on the difference between (more precisely on the ratio of) $1/T_{h_1}$ and $1/T_{\theta_1}$. If $1/T_{h_1}$ is small and positive, as usually true

for $1/T_{\theta_1}$*, the slow subsidence is essentially removed from the $\dot{h}$ response, which is then similar to that for throttle input (Eq. 3). If $1/T_{h_1}$ is negative the magnitude of the subsident contribution is increased and the speed bleed-off effect eventually produces a reversal in the sign of the $\dot{h}$ response. This is a well-known effect of operating on the "backside" of the thrust-required (or drag minus thrust) curve (e.g., Refs. 2, 3, 4), and $1/T_{h_1}$ is directly related to the slope of this curve at the trim speed. Another, not so well-appreciated, fact is that $1/T_{h_1}$ and $1/T_{\theta_1}$ can combine to limit the peak (short-time) $\dot{h}$ response to values considerably less than $U_0\theta$ (Ref. 2), the truly decoupled value (i.e., when $1/T_{h_1} \doteq 1/T_{\theta_1}$. Finally we should note (Eqs. 1 and 3) that the values of $1/T_{h_1}$ and $1/T_{\theta_1}$ cannot be varied independently without also modifying the "inherent" attitude numerator; i.e., the basic derivatives, X_u, Z_u, X_w, Z_w all appear in both ω_θ^2 and $1/T_{h_1}$.

*Considering exact factors, $1/T_{\theta_1}$ can in some cases become negative, and this poses divergence problems for "tight" control of attitude. However such negative values of $1/T_{\theta_1}$ are usually incurred by artificial augmentation of $1/T_{h_1}$ (see Ref. 2) and seldom appear in "natural" STOL airplanes.

SECTION III

EXPERIMENTAL DESIGN

The experimental design reflects the theoretical background exposed in the preceding section. In general, the effects of the various degrees of dynamic and control coupling on manual path control were explored, independent of short-period characteristics, using selected variations in the dynamic and throttle control coupling terms. These variations were accomplished, respectively, through changes in the incremental drag with angle of attack, X_w, and in the thrust inclination. The vertical force change due to speed, Z_u, was maintained at a fixed value throughout the test.

Such changes in coupling terms effectively simulated modification of the aircraft's "total" trim lift/drag characteristics. "Total" in this case refers to the combined aerodynamic and thrust forces. Since the trim characteristics are strongly configuration related, the cross section of parameter variations are considered somewhat equivalent to various medium weight transport aircraft types having different lift/drag characteristics but trimmed at the same flight conditions (e.g., along a −7.5 deg glide slope at 60 kt).

The NASA Ames Research Center S-16 three-degree-of-freedom moving-cab transport simulator was used to provide a limited but realistic motion environment. Conventional transport instrumentation and controls (i.e., control stick and rudder pedals) were employed with basic "raw" guidance information furnished by standard crosspointed needles. A glide slope beam of ±1 deg in depth and a localizer beam of ±3 deg width were simulated; these correspond to an ILS instrument sensitivity of one-half degree per dot glide slope error and three degrees per dot localizer error.

A. TASKS AND TEST MATRIX

A simulated straight-in instrument (ILS) landing approach was the single task performed by the pilots during this study. This approach was initiated on the localizer beam from an off-nominal glide slope situation which corresponded to a path parallel to and 100 ft below a −7.5 deg ILS beam at about a 1500 ft altitude. The initial trim speed was 60 kt. This intentionally-biased starting point in position required a corrective maneuver by the pilot similar to that associated with a normal glide slope intercept. This low condition was indicated by the ILS needles and the pilots were requested to correct the indicated off-condition as quickly as possible. In addition, they generally introduced their own disturbances, offsets, and abuses to aid their evaluation. The lateral ILS task was simply to maintain the localizer beam.

Visual flight was encountered at an altitude of 250 ft which simulated a Category II IFR approach situation. The nominal runway threshold for this −7.5 deg glide slope occurred at an altitude of 35 ft. On breakout the pilots continued the approach visually through final flare and touchdown.

The continuous random turbulence used in this study conforms to the Dryden turbulence forms given in Refs. 9 and 15. Both translational and rotational gust components about longitudinal and lateral axes were introduced. The level of turbulence provided corresponded to a vertical rms gust, $\sigma_w = 3$ ft/sec, based on an average altitude of 500 ft. (Additional specific details are given in Ref. 1.)

The matrix of test configurations examined in this experiment are given in Table 1. The dimensional derivations and the effective linear dynamic characteristics indicated in the table are based on constant coefficient perturbations about the 60 kt nominal trim condition. The vehicle dynamics and coupling change significantly for large speed or angle-of-attack variations from nominal trim, since the actual simulation longitudinal equations were nonlinear (see Appendix A and Ref. 1 for more details).

The particular "nominal' conditions* shown in Table 1 were selected to provide a representative cross section of STOL-type transport vehicle dynamic and control characteristics. In particular, the basic value of X_w and the resulting dynamics of Conditions 1-6 are nominally typical of a tilt wing propeller STOL (e.g., for XC-142 STOL mode, $X_w \doteq .02$), while Conditions 7-12 are more representative of current thrust augmented vehicles (e.g., for augmentor wing concept, $X_w \doteq .14$). Conditions 13-18 represent an extreme of the trend established by the first two sets.

The path control characteristics (i.e., u and $\dot{h}$ responses) for the throttle were governed by the effective thrust inclination, which was varied from the near vertical (90 deg) and from the near horizontal condition for each basic dynamic configuration. The attitude control response, as noted previously, was held constant. In selecting the thrust angle, certain levels of coupling between the speed and altitude rate or flight path were desired. That is, the responses were either coupled (i.e., both u and $\dot{h}$ had essentially the same response for a given input) or purified (decoupled, i.e., throttle produced either u or $\dot{h}$ response). The coupling occurs both from aerodynamic aspects (i.e., through variation in X_w and Z_u terms), static control (i.e., $X_{\delta_T}/Z_{\delta_T}$) derivatives, and combinations of both, as illustrated in the expressions for $1/T_{u_\theta}$ and $1/T_{h_\theta}$ (Eqs. 4 and 5). The "odd" thrust inclination of 63.5 deg was deliberately chosen to make the $1/T_{u_\theta}$ zeros cancel an appropriate pole.

As a final comment on the experimental design, note the variation evident in the values of the backside parameter, $1/T_{h_1}$ (Table 1). As already observed, it is not possible to make changes in the path coupling characteristics which are independent of the backside parameter. Because previous investigations of limiting $1/T_{h_1}$ characteristics (e.g., Refs. 5 and 6) have been "contaminated" by incidental coupling, we chose to separate both aspects as much as possible. Accordingly, the backside and coupling variation were set to oppose each other. That is, the decoupled denominator dynamics (i.e., $1/T_{\theta_2} > 1/T_{\theta_1}$ and $X_w = 0$) were tested for an extreme backside condition, $1/T_{h_1} = -0.09$, and conversely, the coupled denominator was tested at an extreme frontside configuration, $1/T_{h_1} = 0.21$. By this means, we hoped to determine whether the coupling or

*To provide a direct tie with Ref. 1 and the Appendix A data tables the various "Configuration" numbers assigned during the test program to a given condition are identified.

TABLE 1. TEST CONFIGURATIONS AND RANGE OF VARIABLES*

CONDITION NO.	CONF. NO.	DENOMINATOR		ATTITUDE RATE NUMERATOR†		SPEED NUMERATOR†		THROTTLE SENSITIVITY $Z_{\delta_T}/X_{\delta_T}$ g/in.	THRUST ANGLE ARC TAN $-Z_{\delta_T}/X_{\delta_T}$	X_w
		$1/T_{\theta_1}$ (ζ_θ)	$1/T_{\theta_2}$ (ω_θ)	ATTITUDE $1/T_{h_1}$	THROTTLE $1/T_{h_\theta}$	ATTITUDE $1/T_{u_1}$	THROTTLE $1/T_{u_\theta}$			
1	58, 67	.1	.5	−.09	0	.5	.5	−.146/−.0363	104	0
2	57, 66	↓	↓	↓	.1	↓	NA	−.15/0	90	↓
3	59, 68	↓	↓	↓	.5	↓	.5	−.106/.106	45	↓
4	77	↓	↓	↓	.79	↓	↓	−.075/.13	30	↓
5	75	↓	↓	↓	NA	↓	↓	0/.15	0	↓
6	76	↓	↓	↓	−.59	↓	↓	.075/.13	−30	↓
7	61, 70	.3	.3	−.03	0	.73	.9	−.146/−.0363	104	.1
8	62, 71	↓	↓	↓	.1	↓	NA	−.15/0	90	↓
9	60, 69	↓	↓	↓	.3	↓	.3	−.134/.067	63.5	↓
10	80	↓	↓	↓	.79	↓	.44	−.075/.130	30	↓
11	78	↓	↓	↓	NA	↓	.50	0/.150	0	↓
12	79	↓	↓	↓	−.59	↓	.56	.075/.130	−30	↓
13	64, 73	(.6)	(.5)	.21	0	−.45	3.2	−.146/−.0363	104	.67
14	75, 74	↓	↓	↓	.1	↓	NA	−.15/0	90	↓
15	63, 72	↓	↓	↓	.5	↓	−.166	−.106/.106	45	↓
16	83	↓	↓	↓	.79	↓	+.122	−.075/.13	30	↓
17	81	↓	↓	↓	NA	↓	.5	0/.15	0	↓
18	82	↓	↓	↓	−.59	↓	+.894	.075/.13	−30	↓

*Dynamic characteristics valid for perturbation about 60 kt trim condition. Complete aerodynamic data are given in Appendix A.

†NA in the limit when either X_δ or Z_δ are zero and the time constant is undefined, i.e., for $\theta_T = 90^\circ$, $N^u_{\delta_T} = X_{\delta_T}[s + (1/T_{u_\theta})] = X_w Z_{\delta_T}$; for 0°, $N^h_{\delta_T} = -Z_{\delta_T}[s + (1/T_{h_\theta})] = -Z_u X_{\delta_T}$.

backsidedness had the governing effect and also the degree to which "favorable" thrust inclination and interaction could overcome either of these primary path control deficiencies.

Before starting the primary runs represented by Table 1 and the preceding description of the test conditions, etc., a short series of experiments were performed to "tune" the rate command, attitude hold, inner pitch loop; and to set desirable levels of throttle control sensitivity and power. These experiments and results are described and discussed in Appendices A and B, respectively.

B. PILOTS AND EVALUATION METHODS

Four experienced contractor (McDonnell-Douglas Corp.) test pilots were used in the experiment. Their varied background and flight experience provides a representative sampling of piloting qualification ranging from helicopters to conventional transport. One pilot also has extensive flight experience in a deflected slipstream type STOL aircraft. For reference, a synopsis of the pilots' backgrounds and experience is given below; a more complete summary is provided in Ref. 1.

Pilot	Airplane-Type Experience
A	Extensive fighter (F-4 series); moderate STOL (Brequet 941).
F	Extensive large multi-engine airplanes (bombers and jet transports).
J	Current jet transport with Navy fighter background; substantial helicopter time.
K	Current jet transport with Navy fighter (A4D, and F-8U series) background.

Each pilot was given a general description of the experiment at the beginning of his participation in the program. Pilots were instructed to fly first one technique, $\dot{h} \rightarrow \delta_T$ (STOL), then the other, $\dot{h} \rightarrow \theta$ (CTOL); however, they were free to consider other methods of control also. The pilots were asked to comment on and separately rate, using the Cooper-Harper Scale (Ref. 16), the flying qualities associated with ILS glide path control, ILS speed control, and visual flare. An overall rating was also solicited. Appendix A contains the pilot briefing forms and statements actually used.

SECTION IV

RESULTS AND DISCUSSION

The pilot ratings for each of the conditions tested (given in Table A-7, Appendix A) show a considerable scatter, undoubtedly influenced by the limited training time available to overcome the background-related biases of the subject pilots. That is, as later discussed in more detail, a given configuration was judged more harshly by those pilots unfamiliar with the particular control technique required (for best results). While increased familiarization time in the simulator would probably have produced more uniform results, there would still be some residual (statistical) scatter. As a matter of fact, a comparison of the present data trends with those from past investigations shows that the observed data variances are not much different when only the "static" coupling parameter, $-1/T_{h_1} = (g/U_o)(d\gamma/dU)$, is considered. This "conventional," single-factor correlation (Fig. 2, more fully discussed below), which is clearly inadequate for defining flight path problems, sets the stage for the later examinations of our data which show the more governing role of other configuration parameters and control factors.

A. "CONVENTIONAL" CORRELATIONS

The overall influence of the conventional backside parameters, $1/T_{h_1}$, or its equivalent flight path stability parameter, $d\gamma/dU$, on handling qualities (i.e., in Cooper-Harper rating units) is summarized in Fig. 2 (taken largely from Ref. 2). For compatibility with the older (Ref. 2) data for conventional aircraft, the present data trends shown by the faired boundaries are only for thrust inclination near horizontal (i.e., $-30^\circ \leq \theta_T \leq 30^\circ$). The three values of flight path stability tested in the present investigation cover a broad range which includes conditions roughly equal to the Level 3 and Level 1 boundaries prescribed in MIL Spec F-8785B(ASG) as well as a very stable situation where $1/T_h = 0.21\ \text{sec}^{-1}$. This latter stable flight path configuration effectively represents a vehicle having an automatic speed control based on an angle-of-attack feedback. In this "ideal" case the feedback angle of attack activates a horizontal force which is applied along the vehicle's stability axis.

As a general comment, Fig. 2 shows that the current applicable (i.e., for the thrust axis near horizontal) results and those obtained from several other sources are in reasonable agreement from the standpoint of the deterioration of pilot rating with the change in the backside parameter. In effect, the current results do not contradict the findings of previous investigations relative to the significance of the backside parameter, but they do suggest that part of the variation evident in pilot opinion stems from the other factors involved. Among these are pilot preference for a given control technique which may not be the best, and configuration aspects reflected in the associated effects of thrust angle and other couplings. In fact, these, rather than backsidedness *per se*, may be the central issue in pilot opinion.

As inferred above, pilot preference and familiarity with the so-called STOL or backside technique where throttle is used to control path [$\dot{h} \rightarrow \delta_T$, $u \rightarrow \theta_c(\delta_s)$] was a significant factor in these experiments, to be expanded upon in later discussions. However, at this point it is worth noting that the so-called backside (STOL) technique is increasingly superior to the conventional control technique as $1/T_{h_1}$ becomes more negative. The implication is that the throttle is then used exclusively as a means of controlling path, and that attitude is used only as necessary to regulate speed errors. In fact, some of the pilots' comments show that at these backside situations they do not attempt to control speed with the throttle as a means of stabilizing the speed divergence. Instead, they employ stable $\dot{h} \rightarrow \delta_T$ and avoid the more demanding task of controlling the speed divergence associated with the backside condition. The disadvantage of using this strategy is the normally more sluggish response of flight path to throttle.

B. OVERALL CORRELATIONS

The total results (i.e., all thrust inclinations) in Fig. 3 show that both thrust inclination and control technique are important factors, and both may have a significant effect on path control as evident by the pilot rating trends. Static flight path stability alone (i.e., $1/T_{h_1} > 0$) is not sufficient to indicate good or bad ratings; for example, good and bad ratings are evident at each of the backside levels, depending on the thrust inclination and pilot's control technique. (The symbols and associated code identify the actual techniques used by each pilot for a given condition.) In fact, at the extreme backside configuration, $1/T_{h_1} = -0.09$, and thrust angles near 90 deg, almost satisfactory (PR $\doteq$ 4) pilot ratings are evident for Pilot J, who was experienced with and preferred the STOL technique. This is indicative of the uniform improvement in the rating levels and trends as the thrust inclination increases positively from 0 to 90 deg. These trends with thrust inclination are well defined for each situation, although there is evidence of a reasonable scatter among individual pilots.

To explain these trends we will now consider those aircraft parameters and configuration-related aspects which produce coupling of the flight path/speed responses. This was, of course, the purpose of the experimental design reflected primarily in the three baseline configurations (Parts a, b, and c of Fig. 3) which were tested. These three reflect characteristic response properties which include variations in both the (static) flight path stability and in the degree of coupling between the speed and path responses.

For example, the extreme backside configuration (i.e., $1/T_{h_1} = -0.09$) is decoupled dynamically because $1/T_{\theta_1}$ and $1/T_{\theta_2}$ are separated. This means that speed and flight path responses to inputs (i.e., attitude or thrust changes) potentially have different dominant response times. In particular, for an attitude change, speed will respond more slowly than flight path, the two responses being governed, primarily, by T_{θ_1} (speed) and T_{θ_2} (flight path). The value of $1/T_{h_1}$ does not affect these characteristic response times. In extreme contrast, the frontside configuration (i.e., $1/T_{h_1} = +0.21$) is strongly coupled dynamically, with both path and speed responding at the

same frequency and sometimes (depending on thrust inclination) with unconventional phasing (discussed more fully below). The median configuration shows similar but more moderate coupling.

In summary, the three baseline configurations provide various inherent degrees of coupling and associated levels of flight path stability, either of which tend to restrict control of the path variables with attitude commands (i.e., through the stick). Thus, the key to successful path regulation depends on the effective use the pilot can make of the auxiliary control — the throttle (i.e., thrust). This, in turn, depends on the thrust inclination, which may have either a favorable or adverse effect on the speed and flight path coupling.

In the following, we will consider each baseline configuration separately, showing first the thrust inclination effect on pilot rating and, secondly, the part that control technique plays in pilot's opinion. From these results we will infer:

a. Whether flight path stability or coupling factors govern the ratings.

b. How, and to what extent, thrust inclination affects pilot's use of the throttle and path control technique.

c. How, and to what degree, thrust inclination can interact to purify the basic speed and flight path responses.

1. Baseline Configuration (a) — Extreme Backside, $1/T_{h_1} = -0.09$

This condition, as noted several times previously, is somewhat more adverse than the Level 3 requirements of Ref. 9. Consequently, it is not surprising that in general the ratings are relatively poor, particularly when either the conventional control technique is used or when the thrust inclination is near the horizontal (aligned with the X stability axis). To expand on these preliminary observations, we will now consider in some detail the two thrust inclination conditions — near the horizontal and near the vertical.

a. <u>Near Horizontal Thrust</u>. Figure 3a shows that the STOL technique $[\dot{h} \rightarrow \delta_T,\ u \rightarrow \theta_c(\delta_s)]$ is clearly the more suitable method from an overall handling qualities viewpoint. However, even in this case the familiarity of the individual pilot with this technique was a reasonably strong factor in the ratings, and this is reflected by the scatter. Nevertheless, there is a strong trend which is indicative of the superiority of this technique. In fact, the pilots did not feel that the CTOL technique, where attitude is used to control flight path, was practical because of difficulty in controlling the speed divergence. For example, Pilot A

noted that "...primarily speed goes to pot so quickly flying glide path...even using the throttle when speed is deteriorating doesn't help much...." This observation is in keeping with the calculated responses (to attitude commands) shown in Fig. 4.

It is worth noting, however, that proper selection of trim power or slight increases in speed (i.e., to 65 kt) greatly improved the ability of the pilot to use the so-called CTOL technique. To some extent, the pilot was effectively beating the game because, by increasing the speed to the 65 to 70 kt condition, there is a significant improvement in the path control characteristics. In particular, both the coupling and the flight path stability improve; that is, the flight path stability becomes greater and the degree of decoupling increases. This is a consequence of the mechanization of the simulator which was realistic and provided the proper changes in the stability derivatives as a function of speed and angle attack. Thus, the basic characteristics depicted in Fig. 4 are only true if the 60, kt, 7-1/2 deg glide slope situation is maintained. However, it is significant that even the 5 kt increase in speed made little difference to most of the pilots, although Pilot K did rate the CTOL technique as acceptable (PR = 5) for one run. Perhaps it is more significant to note that on the corresponding runs at either +30 or −30 deg thrust inclination, where the speed was closer to 60 kt, his CTOL ratings were unacceptable (PR ≐ 8, 10).

Returning now to the STOL technique and the rating therefor, it is pertinent to examine the basic criticism of this configuration when the thrust was near horizontal. Path control with the STOL technique is considered unacceptable (PR > 6-1/2), particularly when the thrust inclination was exactly zero. Here, the pilots felt that the basic flight path response to throttle was much too sluggish for good control. This poor response of $\dot{h}$ is apparent from the time histories given in Fig. 5. For example, note that at 0 deg thrust inclination, the initial $\dot{h}$ response to thrust command is very low. This stems basically from the fact that the thrust inclination does not aid the initial transient response. In effect, speed builds up first, producing an increased lift ($Z_u u$) which finally results in rate of climb after a noticeable time delay. In transfer function terms, the altitude numerator first order, $1/T_{h_\theta}$, is of such high frequency that it affords no cancellation as in Eq. 6. Thus, the climb response is dominated by the <u>two</u> aperiodic roots, $1/T_{\theta_1}$ and $1/T_{\theta_2}$. Conversely, the speed response is dominated by a first-order mode, $1/T_{\theta_1}$, because of the near cancellation of the pole, $1/T_{\theta_2}$, with the numerator, $1/T_{u_\theta}$. The difference between $\dot{h}$ and $\dot{u}$ response to the throttle input is effectively a time delay.

Thus, while the characteristic modes, $1/T_{\theta_1}$ and $1/T_{\theta_2}$, are separated in a dynamic sense, the responses to throttle, excluding the small time delay, are essentially coupled. In effect, the pilot must depend on the speed buildup as a means of achieving flight path corrections. Such being the case, the pilot is confronted not only with a relatively sluggish (low frequency) flight path response but also with speed changes at the same time and rate (approximately). Thus, he cannot provide separation of the two responses in a clear and concise manner.

As the thrust inclination is increased to 30 deg, there is a significant improvement in the ratings. This improvement stems directly from the improved flight path response due to the vertical component of the thrust inclination. From the standpoint of the numerator and denominator terms that are involved, what has occurred is simply that the numerator term, $1/T_{h_\theta}$, is at a low enough frequency that it tends to cancel some of the adverse lag introduced by the two roots, $1/T_{\theta_1}$ and $1/T_{\theta_2}$. Accordingly, the $\dot{h}$ response is no longer totally dependent on the axial force and the speed buildup but is improved by the initial Z_{δ_T} effect. This apparently accounts for the pilot's improved ratings, despite the basic thrust-induced coupling between $\dot{h}$ and u (see Fig. 5) which still remains similar to that at 0 deg inclination.

In contrast to the above, the improvement reflected by several of the pilots for the −30 deg situation requires a more involved explanation. In the first place, there is now a significant delay in the $\dot{h}$ response to the throttle input, as evident from Fig. 5. Consequently, we would anticipate a correspondingly detrimental effect on the pilot's rating. The observed improvement in rating can be partially explained by the fact that two of the pilots tended to increase their trim speed and thrust, thus effecting an improvement in the basic responses as discussed above. More important, however, the pilots' comments indicate that they discovered they had very precise and good speed control with the throttle, without attendant significant flight path changes (see Fig. 5). Accordingly, the pilots apparently used the delay in flight path response to their advantage and tended to regulate speed (rather than flight path) with the throttle for short-term control, although for the long term, flight path changes were made with the throttle. In effect, the pilots apparently used the CTOL (rather than STOL) technique for short-term regulation about the desired glide path. This technique was made feasible by the effective control-induced decoupling between u and $\dot{h}$ which permitted sufficient u control with throttle to effectively put the aircraft on the front side.

This case shows, therefore, that with small effective downward thrust inclinations which purifies u control, the speed bleedoff aspects of extreme backside operation are amenable to conventional control techniques. On the whole, however, effective upward thrust inclination (and STOL technique) produces somewhat better ratings.

b. Near Vertical Thrust. Figure 3a again confirms that the STOL technique is preferred particularly when thrust angle is near 90 deg. Furthermore, there is a significant improvement in the ratings over the near horizontal thrust conditions previously discussed. The ratings approach the satisfactory level (PR = 3.5) for those pilots more familiar with the STOL techniques (e.g., those with helicopter experience and/or Navy flight background). The best ratings were obtained at 90 deg, where (Fig. 5) there is zero speed response to the throttle input.

Decreasing or increasing the thrust angle from the 90 deg point resulted in degraded ratings. Increasing the thrust angle beyond 90 deg produced the more rapid deterioration, as evident from Fig. 3a. The major criticism directed at this configuration was the aircraft's tendency to slow down for positive throttle inputs (Fig. 5), e.g., when arresting sink rate. Correcting this adverse speed change required the pilot to use attitude changes which opposed the flight path corrections, and the tendency to slow down resulted in a more critical angle-of-attack situation. For example, to regain the speed loss resulting from a positive flight path correction requires the pilot to pitch over. This tends to increase the speed but at the same time nullifies part of the desired flight path correction (see Fig. 4). This adverse interaction between flight path and speed often resulted in excessive attitude excursions and throttle motions resembling a PIO. This multiple control PIO tendency was noted most by the pilots who were less familiar with the so-called "STOL technique," e.g., Pilots A and F. In summary, this condition suffered from an incorrect (sign) u response rather than from dynamic coupling which was still small.

A decrease in the thrust angle, as noted above, also had an adverse effect on the rating and, in general, the pilot's overall control of path and speed. Here, the increased coupling between speed and path response, which was the main and primary objection, is evident in the computed time response of Fig. 5 (for 45 deg). Pilot J, who was more experienced in the STOL technique, was most critical of the coupling, as evident from the deterioration in his rating at the 45 deg angle.

As a final comment, note that there is a favorable improvement in handling quality ratings with increasing thrust inclination between 0 and 90 deg. This trend is well defined and appears continuous for the data shown. This infers that favorable improvements in handling qualities can be achieved at strong backside situations by essentially increasing the thrust angle.

2. Baseline Configuration (b) — Moderate Backside, $1/T_{h_1} = -0.03$, with Coupling ($1/T_{\theta_2} = 1/T_{\theta_1}$)

Figure 3b shows the results obtained for the moderate backside configuration ($1/T_{h_1} \doteq -0.03$) for which the basic modes are coupled (i.e., $1/T_{\theta_1} = 1/T_{\theta_2}$). Again, regardless of the thrust inclination, the STOL (backside) technique was preferred by the pilots. Also, as previously, the CTOL technique was considered unacceptable primarily because of excessive speed response to attitude (Fig. 4) and resulting speed control problems with the throttle. Thus, auxiliary speed control with the throttle was a limiting factor for CTOL operation, as usual for most backside configurations.

a. Near Horizontal. There is a general improvement in the rating levels for this configuration relative to the extreme backside configuration of Fig. 3a. This improvement can partly be attributed to the more favorable backside condition, since the pilots in general appreciated the more manageable speed control. Both backside conditions exhibit similar path/speed coupling, but the moderate backside condition in general shows faster responses (compare Figs. 5 and 6). Because of the increased response, the ratings show a significant improvement over those in Fig. 3a. This general improvement also tends somewhat to suppress the rating effects of variations in thrust inclination which, as shown in Fig. 3b are relatively small. That is, the faster response level is less sensitive to given improvements than the slower, more critical responses associated with the Fig. 3a conditions.

b. Near Vertical Thrust. Generally, satisfactory ratings are evident for most of the pilots, using the STOL technique with the near vertical thrust configuration (Fig. 3b). As evident from the time responses of Fig. 6, the u and $\dot{h}$ responses are essentially decoupled despite the basic coupling afforded by $1/T_{\theta_1} = 1/T_{\theta_2}$. This decoupling is sometimes due to the small magnitude of the u response, relative to $\dot{h}$ (e.g., 63.5 deg) and sometimes to the slower relative dynamics (e.g., 90 deg). With the thrust inclination at 104 deg (i.e., pointed backwards), there is a sharp degradation in the ratings of around 1 to 2 points. This rapid change stems from

the adverse speed change effect due to the throttle, as discussed for the similar condition in Fig. 3a.

The best ratings, overall, occurred with the thrust angle in the neighborhood of 63.5 deg, which was selected to afford pure cancellation between numerator and denominator terms and identical first-order response modes for both $\dot{h}$ and u (see Fig. 6 and Table 1). This is a particularly interesting configuration, because while the $\dot{h}$ and u responses are thus apparently strongly coupled dynamically, they are in fact decoupled because of their relative magnitude, as already noted.

At the 90 deg condition, the adverse speed effect is relatively small. However, it was noted by the pilots and considered to be unfavorable, and thus the ratings shown in Fig. 3b are in general slightly degraded from the optimum level which occurred near 63.5 deg.

In earlier discussions we emphasized the dynamic response coupling and separation aspects. However, we have now broadened the coupling considerations to include the equally important response magnitudes of $\dot{h}$ and u. Furthermore, we infer the additional consideration that the two responses should, in all cases, be favorably connected. By favorable, we mean that for positive $\dot{h}$ response there is either a neutral change in speed or a favorable increase in speed. Adverse speed changes (i.e., reduced speed for a positive $\dot{h}$ increase) will result in degraded ratings.

3. **Baseline Configuration (c) — Frontside,** $1/T_{h_1} = +0.21$, **with Strong Coupling** (Complex $N^{\dot{h}}_{\delta_e}$)

The results of the extreme frontside configuration given in Fig. 3c provide the best indication of the adverse effects of dynamic coupling on the pilots' overall controllability of the path modes. Here, the degree of coupling works to restrict the pilot's ability to properly use stick and throttle in combination; that is, he cannot partition, or separate, the response manually.

a. Near Horizontal. The strongest criticism of these configurations was expressed when the pilots attempted to control the two path variables, u and $\dot{h}$, by either of the two-control strategies. In particular, this resulted in the following comment by Pilot A.

> "This last configuration has me completely confused....very difficult to sort out what effects the throttle has on the flight path or speed."

As a consequence of the difficulties reflected by these comments, all the Fig 3c ratings for either the STOL or CTOL control technique were unacceptable. In general, the pilots' major criticism here was that they had no control of speed. In fact, the scatter in the ratings depended strongly on whether the pilot felt he had to control speed in any of the given tasks; in many cases he did not. For example, both Pilots K and F discovered that by using only the stick to control flight path at constant throttle, speed tended to more or less take care of itself (e.g., see Fig. 4 for $X_W = 0.67$) For these two pilots, the configuration was considered nearly satisfactory (PR $\doteq$ 4), although Pilot K had some reservations because there was no positive way of controlling airspeed. In fact, he stated that "attempt to control airspeed was disastrous." Similar attempts to neglect airspeed and control flight path with throttle were not nearly so successful (coupling effects were of course still present — see Fig. 7) as indicated by the generally unsatisfactory ratings.

b. Near Vertical Thrust Angle. Neither combined technique worked too consistently for the near vertical thrust, as indicated by the considerable scatter in the applicable data points (symbols ◺, ⊡ in Fig. 3c). Several pilots again noted that path control with the stick was good as long as no attempt was made to regulate speed. This resulted in the best set of ratings as for the near horizontal thrust. In fact, because thrust control is not being exercised, thrust inclination has no effect as predictable (i.e., regardless of thrust inclination the controlled responses are those of Fig. 4).

In general, the STOL technique produced more consistent data, with better pilot ratings, mainly around the 5 level. The effects of thrust inclination for this technique appear to be surprisingly minor in view of the fairly drastic changes in the relative responses in Fig. 7. However, as noted previously, the pilots had great difficulty in sorting out the response effect of a given input in general, and this confusion may have inhibited their rating discrimination.

For the CTOL technique, normal speed control with the throttle adds to the climb error (see Fig. 7). This fact apparently resulted in the large variation in the ratings shown for this technique. In particular, the best ratings, which were marginally acceptable, occurred when speed control with the throttle was minimal. However, one pilot (A) recognized the reversed characteristics of the u response to throttle and employed the throttle in

the reverse sense. Of course, this now detracts from the $\dot{h}$ response, and the resulting rating (about 4-1/2) is indicative of the confusion involved.

In any event, some of the pilots experienced a strong tendency to oscillate along the path using only stick. Pilot F, in particular, noted the resemblance to pilot-induced oscillations (PIO). Although he attributed these tendencies to problems with pitch attitude control, they are more accurately a reflection of flight path control and the overshoot tendencies of flight path response to attitude (Fig. 4). Similar problems encountered with conventional angle-of-attack autothrottles (which modify X_w as here) are discussed in Ref. 11. Also, the Ref. 10 PIO correlations and criteria boundaries indicate a probably "benign" PIO for the $\dot{h} \rightarrow \theta_c(\delta_s)$ characteristics of these cases.

C. IMPLICATIONS OF PILOT PREFERENCE AND FAMILIARITY WITH STOL TECHNIQUE

A recent STOL flight control system investigation, summarized by Harris in Ref. 12, suggested that pilot preference for the so-called CTOL technique is fundamental; consequently, all aircraft control systems must be configured to maintain the effectiveness of this technique. In particular, Harris states that the desirable situation is completely decoupled so that flight path is a function only of control column inputs, and speed only of the throttle levers. Application of this control-response philosophy could have a significant, if not overwhelming, impact on STOL configurations and control system designs. Accordingly, the aspect of pilot preference cannot be ignored and presents a nagging question relative to STOL aircraft design. In the following we therefore endeavor to briefly consider the above philosophy, and the apparent effects of pilot preference, using the somewhat limited results obtained in the current experiments.

As a starting point we have ordered the abscissae of Fig. 8 according to the flight backgrounds of our participating pilots, starting at the left with helicopter-experienced pilots and proceeding right to transport or conventional aircraft pilots. In this manner we may infer to some degree the individual pilot's preferences, as exhibited by the ratings plotted for the two extreme configurations, and the influence that flight background has on ratings. The most diverse background in the current tests are represented by Pilots J and F, respectively. Pilot J, basically a Navy-trained pilot with extensive helicopter experience and with a personal preference for the so-called backside control technique, is in direct contrast to Pilot F, a highly experienced transport pilot who prefers the CTOL technique. Further, Pilot F felt strongly that STOL aircraft should be controlled in the same manner as contemporary conventional transport aircraft (i.e., as Harris outlined, control column for flight path and throttle for speed).

Pilot K, who also is Navy trained but with limited helicopter and VTOL experience, represents an intermediate, as does Pilot A, who has a diverse background which includes fighters and STOL transport aircraft.

With this background in mind, consider now the rating data shown for thrust inclinations of zero and 90 deg and for the two extreme dynamic configurations (i.e., backside and frontside). The symbols, and associated legend, identify the actual techniques used to obtain these "best" ratings for a given configuration and pilot. For the extreme backside situation of Fig. 8a, we see that the pilots' flight backgrounds do appear to strongly influence their ratings. That is, the ratings clearly indicate a degrading trend for the pilots less experienced with the so-called STOL technique. For example, the helicopter- and Navy-experienced Pilot J ratings are always better than those for the conventional Pilot F. However, at the zero deg thrust inclination even the helicopter pilot considered the thrust response sluggish and unacceptable.

Turning to the extreme frontside condition (Fig. 8b), we see essentially the reverse of the trend obtained for the backside condition. That is, the STOL pilots are now rating the system more adverse than the conventional pilots. This apparently stems from the STOL pilots' insistence on using the dual control technique, where throttle, as a primary control, is used to control $\dot{h}$ and u is controlled by attitude. However, due to the strong interaction between u and $\dot{h}$ responses to the throttle, this technique has limited effectiveness. Part of the problem is due simply to the fact that throttle is considered the primary path controller. Thus, the path and u responses to throttle must be separable to satisfy STOL pilots. This is not true for the conventional pilot, who considers the throttle more of an auxiliary control. Thus, the single $\dot{h} \rightarrow \theta_c(\delta_s)$ loop (symbol ⊙) with no attempt to control (the small) airspeed excursions, which is compatible with the inherent aircraft response (Fig. 4) is natural and preferred. Accordingly, when the conventional pilot discovered the suitability of flight path control with attitude (through elevator), he rated it totally satisfactory.

The major point of the foregoing is that the trends are reversed. We see, therefore, that it is difficult to dictate a single control technique which will be satisfactory for all aircraft configurations or pilots. In particular, pilots who are used to controlling flight path with throttle will, in general, tend to maintain this control technique, regardless of the aircraft's configurations and its limitations. Consequently, where aircraft-related parameters limit the ability to use the pilot's desired technique, he will (at least initially) degrade the vehicle from the standpoint of handling qualities. Therefore, we conclude that arbitrarily setting a given control technique for a particular type of vehicle may seriously limit its initial acceptance by individual pilots. In addition, an arbitrarily set technique, which does not recognize alternative aircraft-inherent possibilities, may unduly complicate the flight control system required (e.g., Ref. 12) for acceptance, even by pilots well versed in the technique.

A number of inferences may be drawn, as follows:

1. For <u>immediate</u> acceptance of the broadest population of pilots the desirable approach is to have a control technique, or a flight control system and aircraft configuration, for which either control technique is suitable.

2. The preferred technique should be dictated by attainable landing performance and safety considerations and not by pilot preference. Pilots should be trained (or retrained), if necessary, in order that maximum potential performance can be reliably achieved.

3. Flight control system complexity and resulting aircraft unavailability may dictate compromises to either of the above two "pure" approaches to the question.

SECTION V

CONCLUSIONS

In general the results of the experiment confirm that the pilot's ability to utilize either of the prevalent control techniques depends on the purity of the responses to individual controls in their assigned role. When corrupting effects are present the relative magnitude of the "secondary" responses should be small and complementary. For example, if throttle is used to increase flight path angle, the associated speed error should be small and preferably positive so that correcting it with a positive (nose up) attitude change adds to (complements) the desired increased climb.

Specific conclusions are:

1. Thrust inclination affects the boundary values of the backside parameter (i.e., $1/T_{h_1}$ of $d\gamma/dU$).

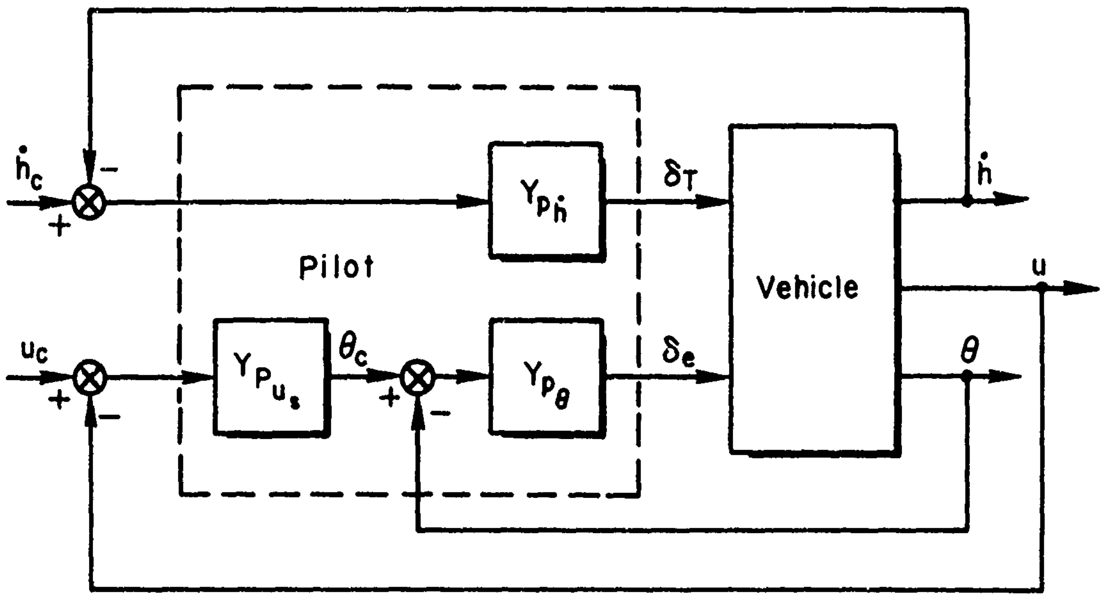
2. Control technique [i.e., either CTOL ($\dot{h} \rightarrow \theta(\delta_s)$; $u \rightarrow \delta_T$) or STOL ($\dot{h} \rightarrow \delta_T$, $u \rightarrow \theta(\delta_s)$)] and pilot familiarity are major factors in STOL handling qualities.

3. The attitude numerator $N^{\theta}_{\delta_e}$ factors fundamentally govern the path control response modes which are essentially independent of the short-period modes. However, the separation or coalescence of the speed and flight path responses to control inputs also depends strongly on the control force inclinations (and moments, neglected for convenience in this effort).

    a. Attitude factor (mode) separation is desired because, by proper selection of thrust inclination, favorable cancellation of modes and purified responses are then possible. As demonstrated by the current results, this cancellation or purification in response has a significantly favorable effect on handling qualities.

    b. Conversely, coupled attitude factors (modes) inherently couple both speed and flight path so that there is little possibility of cancellation by thrust inclination.

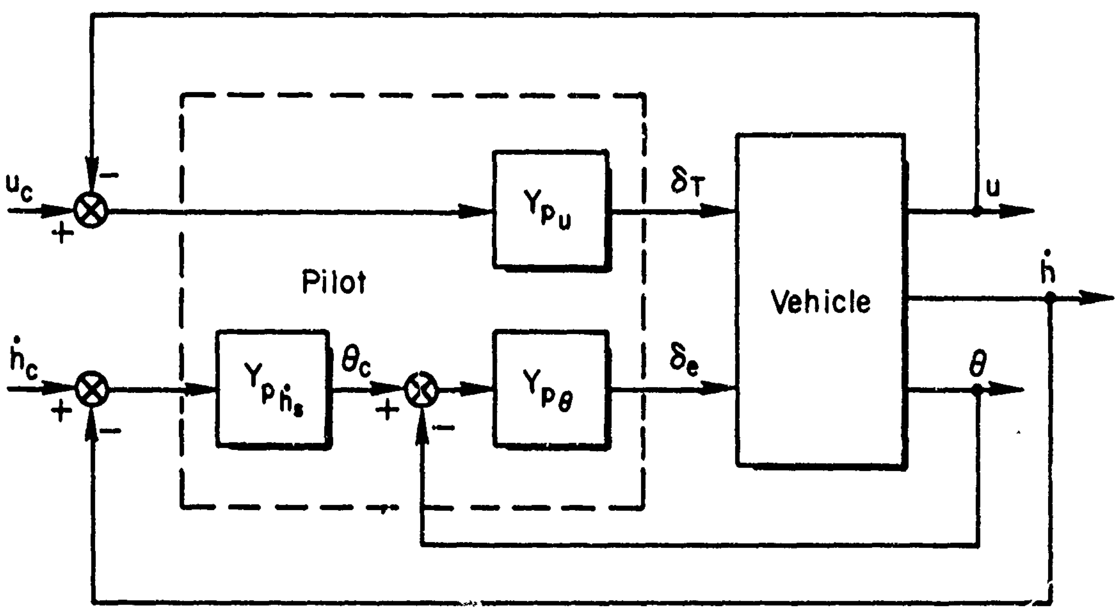
4. The pilot is restricted to single controller techniques for strongly coupled path/speed dynamics. In particular, where the coupling is due to large positive X_w as investigated here, flight path control with stick is the only satisfactory control technique. Since the pilot has no practical means of speed regulation, he has less flexibility in correcting for unusual and off-nominal situations. This implies that an autothrottle (thrust horizontal) concept based on a simple angle-of-attack feedback (i.e., $\alpha \rightarrow \delta_T$) may be unsuitable for STOL application.



a) STOL Technique

$u, \theta \rightarrow \delta_e$

$\dot{h} \rightarrow \delta_T$



b) Conventional Control Technique (CTOL)

$\dot{h}, \theta \rightarrow \delta_e$

$u \rightarrow \delta_T$

Figure 1. Two Piloting Techniques

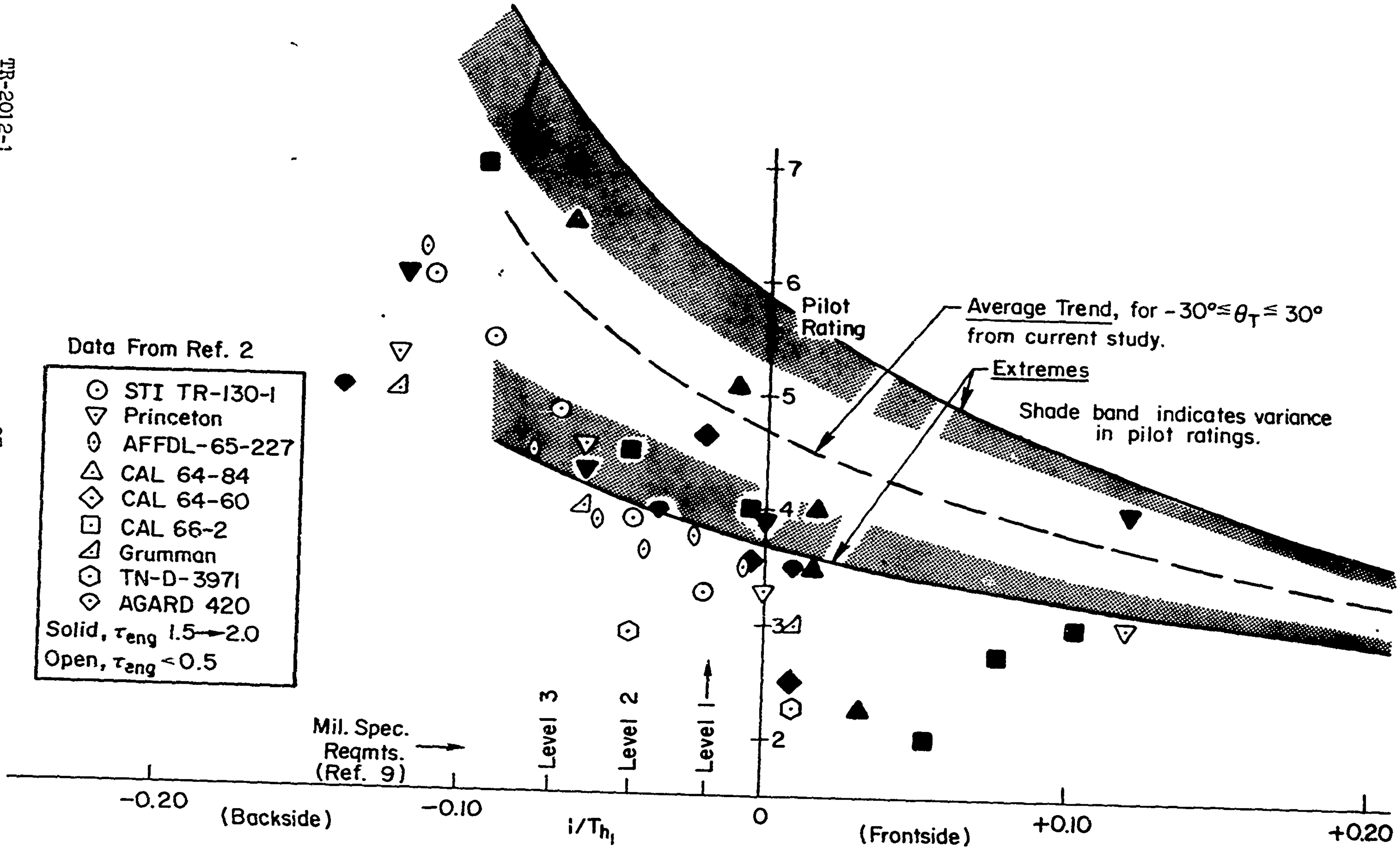
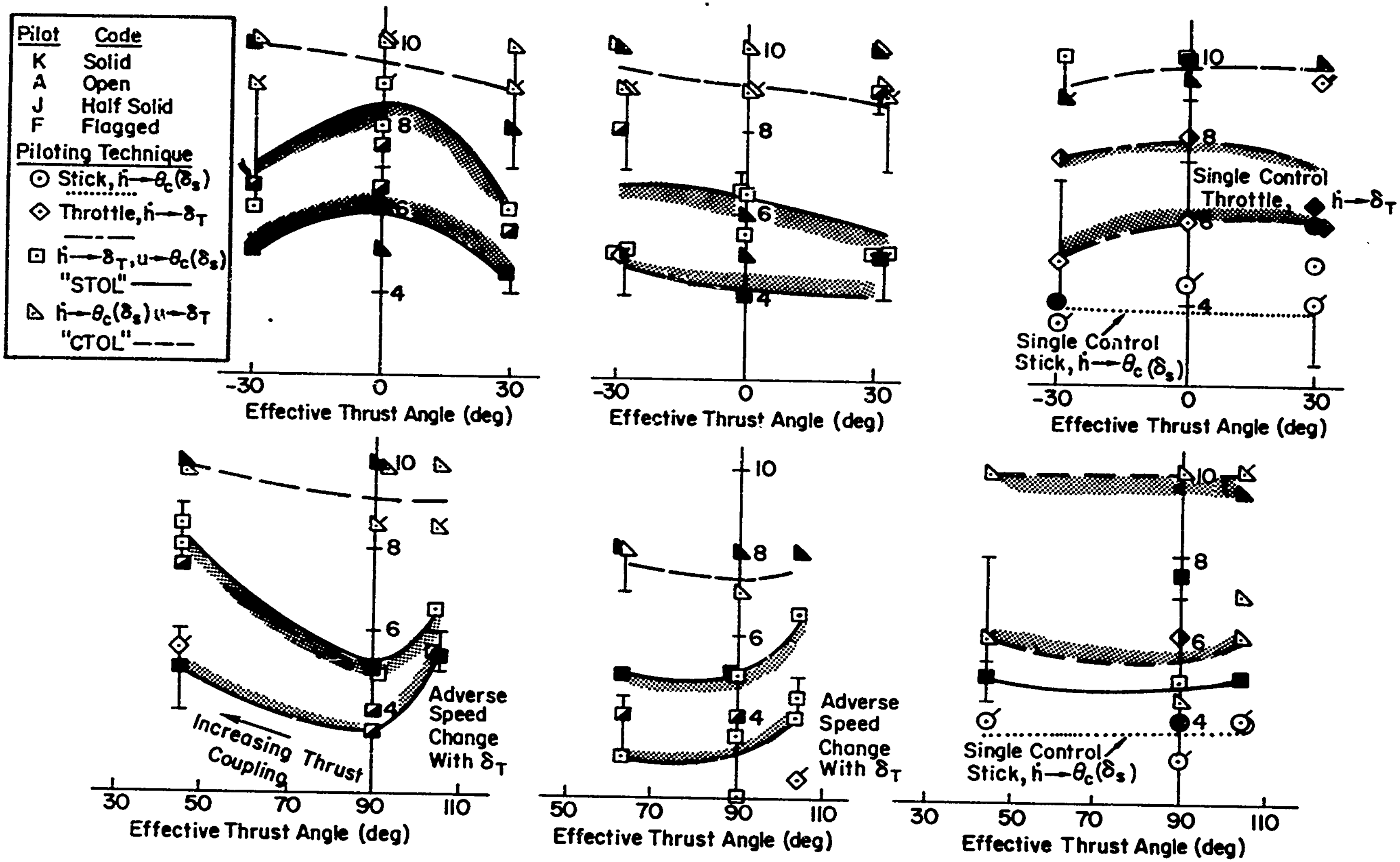


Figure 2. Comparison of Various Backside Data with Mil Spec Requirements and Current Results for Thrust Near Horizontal



(a) Extreme Backside, $1/T_{h_1} = -.09$
Decoupled $N^{\theta}_{\delta_e}$ $(1/T_{\theta_1} \neq 1/T_{\theta_2})$

(b) Moderate Backside, $1/T_{h_1} = -.03$
Coupled $N^{\theta}_{\delta_e}$ $(1/T_{\theta_1} = 1/T_{\theta_2})$

(c) Frontside, $1/T_{h_1} = .21$
Coupled $N^{\theta}_{\delta_e}$ $[\zeta_\theta, \omega_\theta]$

Figure 3. Effect of Various Control and Configuration Characteristics on Manual Path Control

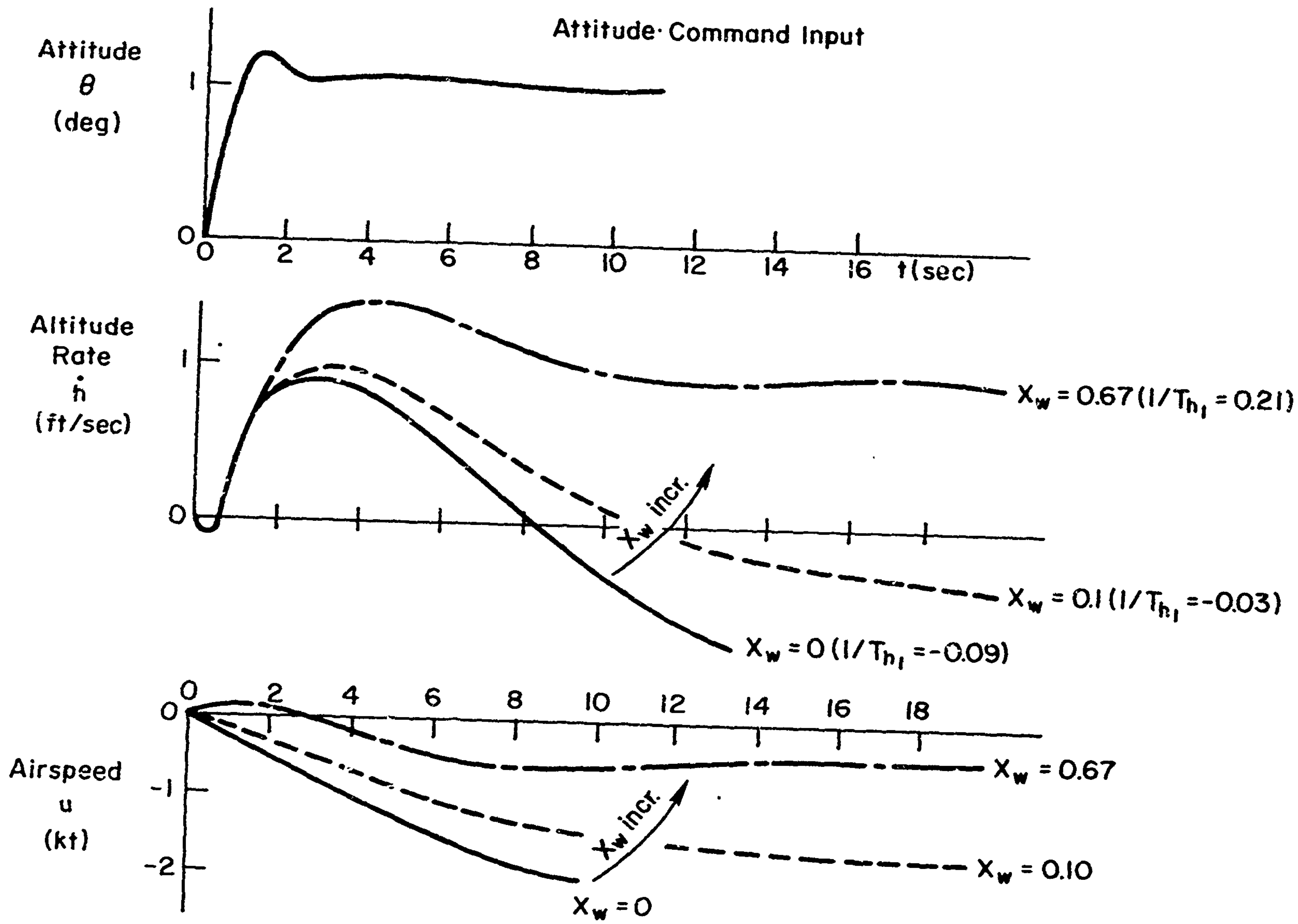


Figure 4. Effect of X_w on Perturbed Path/Speed Responses to Step Attitude Command Input

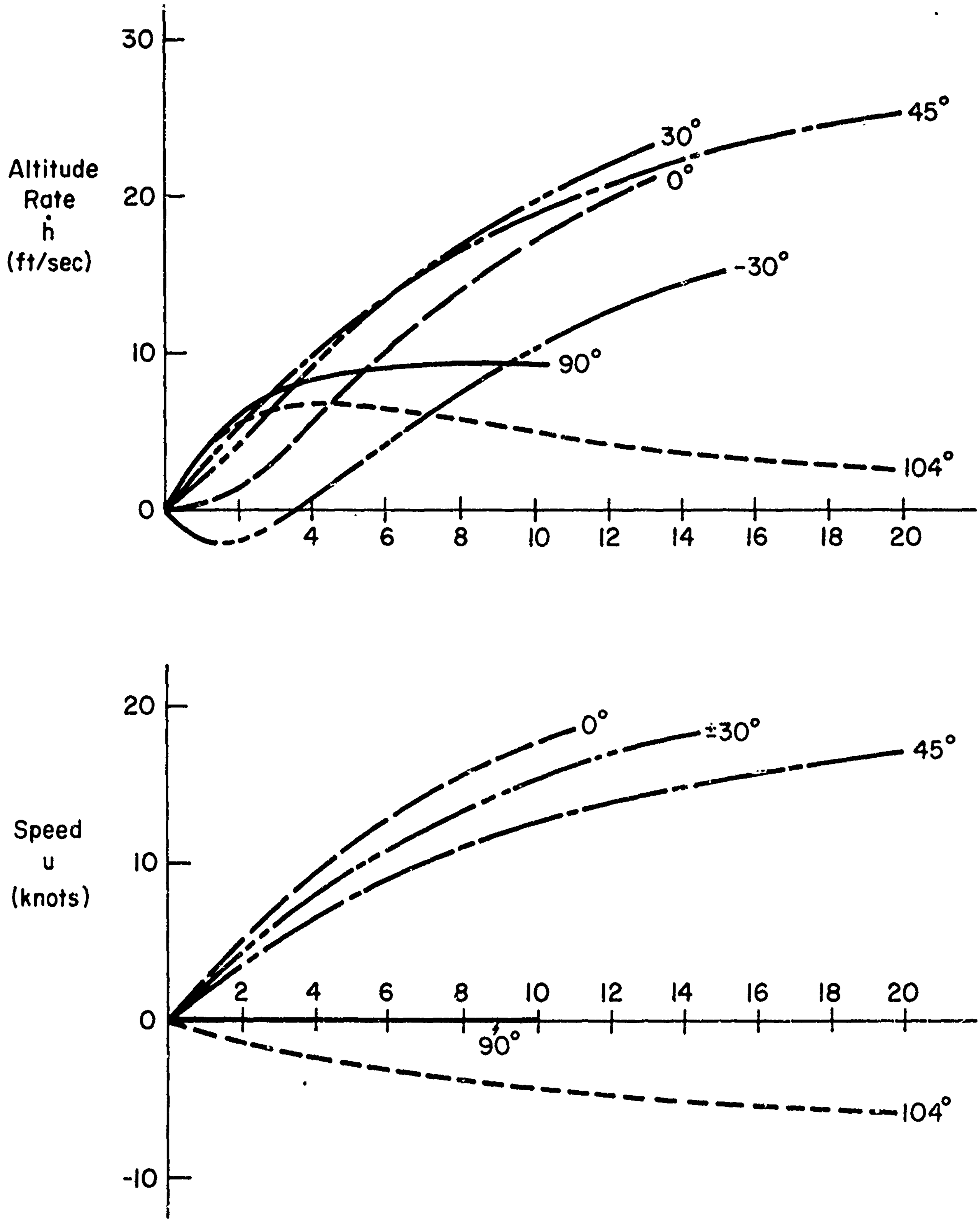


Figure 5. Perturbed Path/Speed Responses to 1 Deg Step Throttle Extreme Backside, $1/T_{h_1} \doteq -0.09$ ($X_w = 0$)

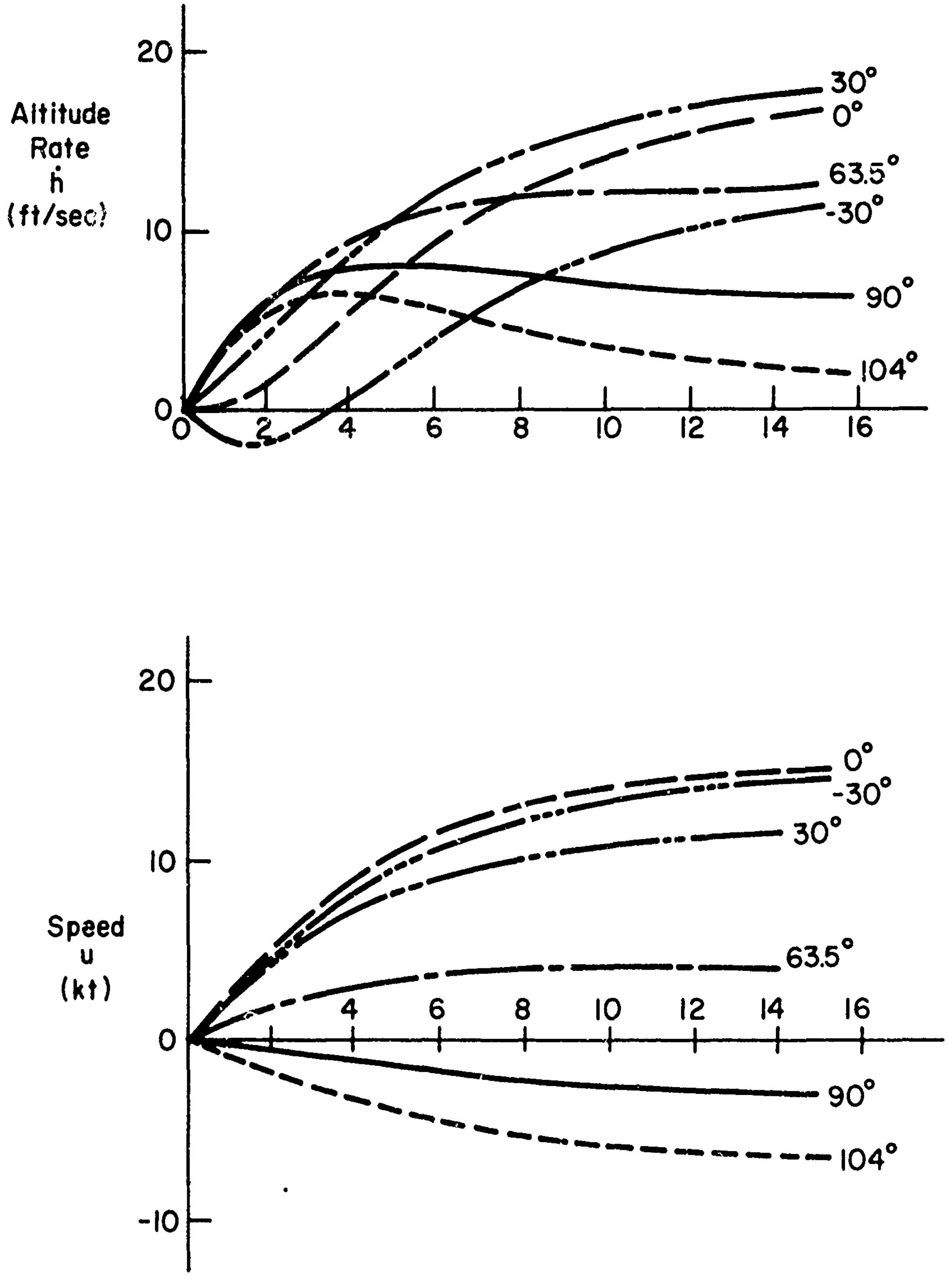


Figure 6. Path Response to Unit Step Throttle; Moderate Backside; $1/T_{h_1} \doteq -0.03$ ($X_w = 0.1\ \text{sec}^{-1}$)

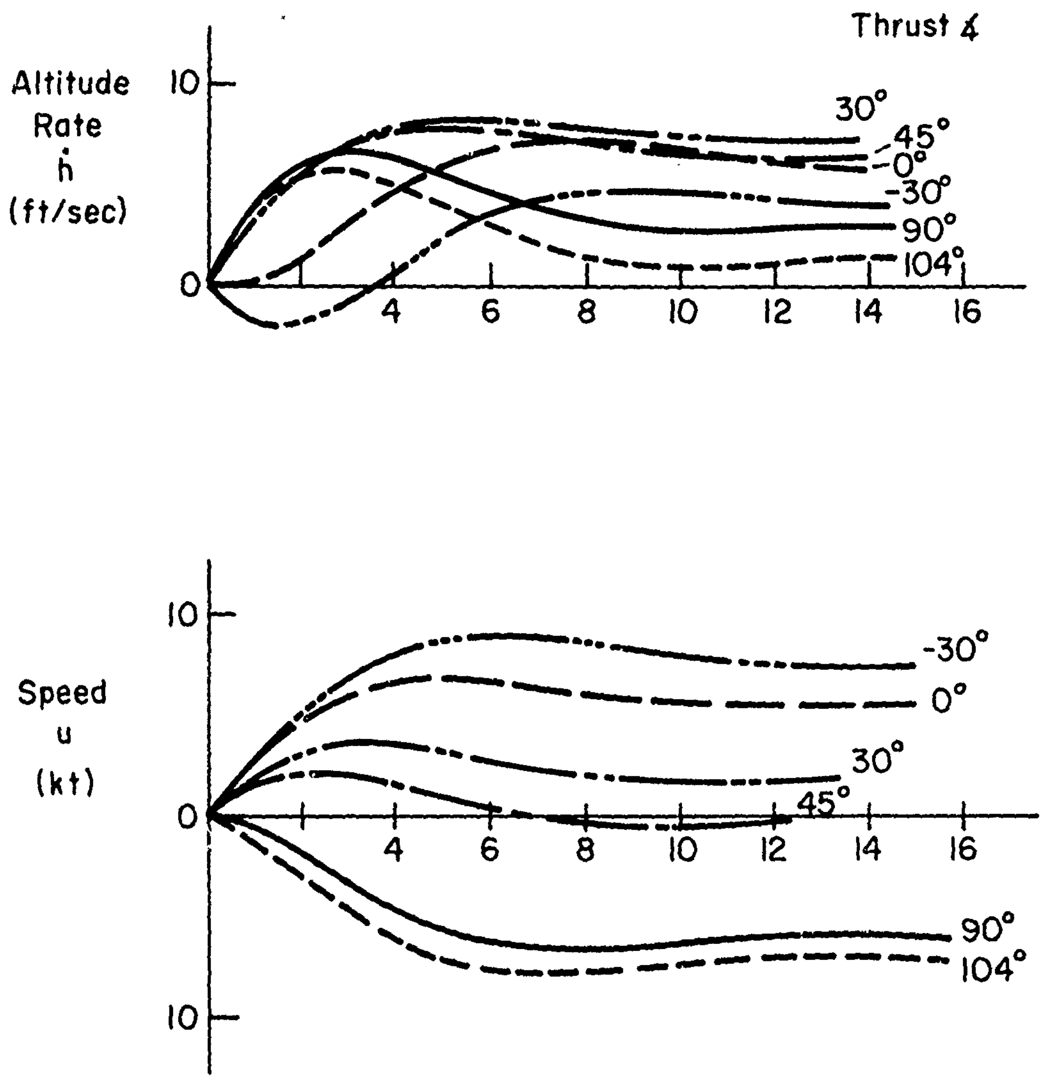


Figure 7. Path Response to Unit Step Throttle; Frontside
$1/T_{h_1} \doteq 0.21$ ($X_w = 0.67$ sec^{-1})

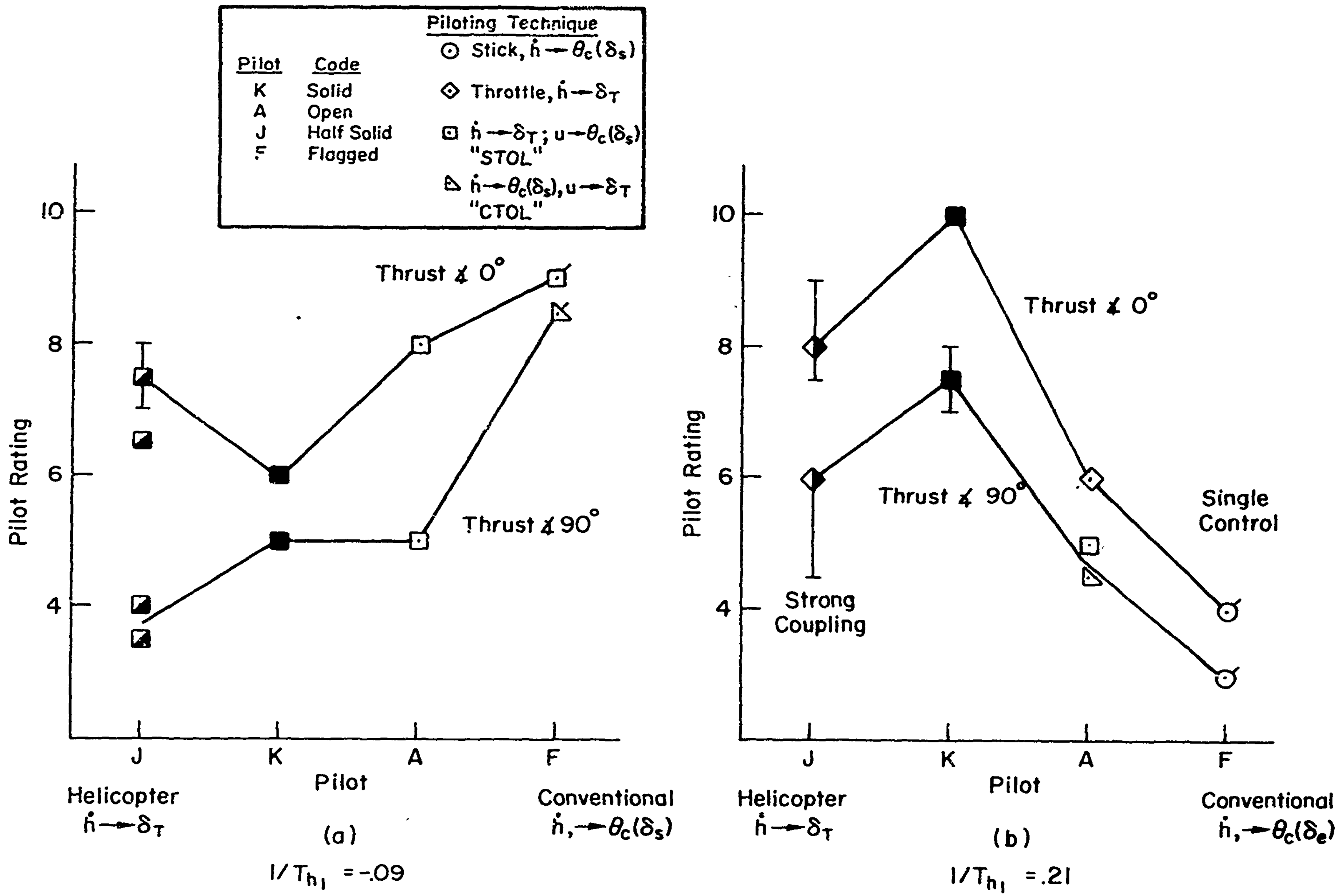


Figure 8. Effects of Flight Background on Ratings

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APPENDIX A

PHYSICAL CHARACTERISTICS, AERODYNAMIC DATA, AND PILOT RATINGS

Tables A-1 through A-4 of this appendix contain the basic physical characteristics, aerodynamics, and equations of motion used for the "Brequet 941" aircraft simulation which was the baseline vehicle used in this longitudinal path control study. Table A-5 gives a listing of incremental changes in the longitudinal aerodynamic data used to modify the "Brequet 941" characteristics. Dimensional stability derivatives based on the 60 kt, −7.5 deg glide slope trim conditions are presented in Table A-6. Table A-7 lists the ratings and limited pilot commentary for the "configurations" given in Table A-6. The configuration numbers correspond to the various condition numbers shown in Table 1 of the text.

Additional details on the simulation are available in Ref. 1.

TABLE A-1

PHYSICAL CHARACTERISTICS OF SIMULATED AIRCRAFT

Weight	W	60,000 lb
Wing Area	S	1,000 sq ft
Wing Span	b	78 ft
Wing Mean Aerodynamic Chord	c	13.0 ft
Rolling Moment of Inertia	I_x	160,000 slug ft^2
Pitching Moment of Inertia	I_y	400,000 slug ft^2
Yawing Moment of Inertia	I_z	600,000 slug ft^2
Product of Inertia	I_{xz}	20,000 slug ft^2
Maximum Thrust (at V = 70 kts)	$T_{max_{70k}}$	31,600 lb
Maximum Horsepower	HP_{max}	10,000 HP

TABLE A-2

CONTROL AND CONTROL FEEL SYSTEM CHARACTERISTICS

Elevator		
Aft Stick Travel	$\Delta_{e_{s_{aft}}}$	7.5 in.
Forward Stick Travel	$\Delta_{e_{s_{fwd}}}$	3.5 in.
Breakout Force	$F_{e_{BO}}$	3.0 lb
Force Gradient	$F_{e_{\Delta_{e_s}}}$	1.8 lb/in.
Gearing	δ_e/Δ_{e_s}	6.0 deg/in.
Rudder		
Pedal Travel	Δ_{rp}	±3.5 in.
Breakout Force	$F_{r_{BO}}$	10.0 lb
Force Gradient	$F_{r_{\Delta_{rp}}}$	18.0 lb/in.
Gearing	δ_r/Δ_{rp}	11.5 deg/in.
Aileron		
Stick Travel	δ_{a_s}	±37.5 deg
Stick Deflection	Δ_{a_s}	±6.6 in.
Breakout Force	$F_{a_{BO}}$	2.0 lb
Force Gradient	$F_{a_{\Delta_{a_s}}}$	0.9 lb/in.
Stick Gearing	δ_a/Δ_{a_s}	6.1 deg/in.
Effective Stick Length		10.0 in.
Propulsion System		
Throttle Lever Travel	δ_t	10 in.
Throttle Gearing	HP/δ_t	1000 HP/in.

TABLE A-3

LATERAL-DIRECTIONAL AERODYNAMIC CHARACTERISTICS*
OF SIMULATED AIRCRAFT

(All derivatives are per radian)

$C_{n_\beta} = 0.63$	$C_{\ell_\beta} = -0.048$	$C_{y_\beta} = -1.50$
$C_{n_p} = -0.055$	$C_{\ell_p} = -1.72$	$C_{y_p} = 0.20$
$C_{n_r} = -1.17$	$C_{\ell_r} = 0.081$	$C_{y_r} = 0.75$
$C_{n_{\delta_a}} = 0$	$C_{\ell_{\delta_a}} = 0.216$	$C_{y_{\delta_r}} = 0.319$
$C_{n_{\delta_r}} = -1.60$	$C_{\ell_{\delta_r}} = 0.0105$	

*Unless otherwise noted on Run Log.

TABLE A-4

NON-VARYING LONGITUDINAL AERODYNAMIC CHARACTERISTICS
OF SIMULATED AIRCRAFT

$C_{m_{\alpha=0}} = 0.081$*	$C_{m_q} = -25.0$/rad
$C_{m_{\dot\alpha}} = -10.5$/rad	$C_{L_q} = 8.0$/rad
$C_{m_{T_c}} = 0$	$C_{L_{\dot\alpha}} = 3.3$ rad

*See equations of motion for modification of $C_{m_{\alpha=0}}$ in ground effect.

TABLE A-5

INCREMENTAL CHANGE IN STABILITY DERIVATIVES

CONFIG.	ΔC_{L_α}	ΔL_V lb/fps	ΔD_V lb/fps	$C_{\dot{D}_{\delta_{3max}}}$	ΔC_{D_α}	$C_{D_{\delta_t}}$	$C_{L_{\delta_t}}$	$\pm\delta_{t_{max_{eff}}}$ inches
51	0.815	89.5	−55	−0.5	2.06	0	0.98	10
52							1.47	
53							1.96	
54							0.73	0.56
55								0.88
56								0.44
57								10
58						0.177	0.71	
59						−0.516	0.516	
60					0.523	−0.326	0.655	
61						0.177	0.71	
62						0	0.73	
63					−5.63	−0.516	0.516	
64						0.177	0.71	
65						0	0.73	
66				0	2.06	0	0.73	
67						0.177	0.71	
68						−0.516	0.516	
69					0.523	−0.326	0.655	
70						0.177	0.71	
71						0	0.73	
72					−5.63	−0.516	0.516	
73						0.177	0.71	
74						0	0.73	
75					2.06	−0.73	0	
76						−0.632	−0.365	
77						−0.632	0.365	
78					0.523	−0.73	0	
79						−0.632	−0.365	
80						−0.632	0.365	
81					−5.63	−0.73	0	
82						−0.632	−0.365	
83						−0.632	0.365	

TABLE A-6

DIMENSIONAL LONGITUDINAL DERIVATIVES OF SIMULATED AIRPLANES

CONFIG.	X_u 1/sec	X_w 1/sec	Z_u 1/sec	Z_w 1/sec	$Z_{\dot{w}}$	Z_q ft/sec	Z_{δ_e} ft/sec^2	$M_{\dot{w}}$ 1/ft	M_α 1/sec^2	M_q 1/sec	M_{δ_e} 1/sec^2
69	−0.10	0.106	−0.4	−0.508	0.0137	3.368	−3.281	−0.00264	−0.2672	−0.635	−0.596
70											
71											
72		0.674									
73											
74											
75		0.007									
76											
77											
78		0.106									
79											
80											
81		0.674									
82											
83											
51	−0.100	0.007	−0.40	−0.508	0.0137	3.368	−3.281	−0.00264	−0.2672	−0.635	−0.596
52											
53											
54											
55											
56											
57											
58											
59											
60		0.106									
61											
62											
63		0.674									
64											
65											
66		0.007									
67											
68											

TABLE A-7

PILOT RATING RESULTS FOR PATH CONTROL STUDY

CONFIG. NO.	PILOT	PILOT RATINGS: OVERALL	PILOT RATINGS: GLIDE PATH	PILOT RATINGS: SPEED	PILOT RATINGS: FLARE	PRIMARY CONTROL: SPEED	PRIMARY CONTROL: GLIDE PATH	MISCELLANEOUS
59	F	5/5,4	5/		4/	δ_T,DDC	δ_e	PR=4 if DDC mechanized better
60		3.5/2.5	3/2.5	3.5	5.5			
61		4/2	4.5					PR=2 if pilot could design DDC
62		2	2			δ_T		
75	J	7.5	8	7		δ_e	δ_T	
76		6.5	7	6	6.5			
77		5.5	5.5	5.5	6			
78		6.5	6.5	6.5				
71								VOID
57								VOID
79		8	8					
57	F	7	7	3				
63		4	5	3	8			
64		10/6.5	10/4		10/8	δ_T,DDC	δ_e	
65		4	3	1		None		Very speed stable
75		4/4	4/4	4		δ_T,DDC		
76		3.5	3.5	3	3.5	δ_T		
77		3.5/3.5	3.5/3.5	3/3	3.5/3.5	δ_T/DDC		
78		3	3	3	3	δ_T		
79		3.5	3.5	3	3			
80		3	3	3	3			
75		10						
78		9						
79		9	7	4/9	10			Speed rating = 4 if at 65 kt
80		9	7	4/9	10			
81		4.5	4	2	4.5	None		
82		3.5	3	2	5	δ_T		
83		2.5	2	2	3	δ_T		
66	K	7 or 5	6	4		δ_e	δ_T	PR=5 for long. overall
66		"stinks"				δ_T	δ_e	
67		2	5.5	4.5		δ_e	δ_T	
67		5	6	4	6	δ_e	δ_T	
68		"Technique is unusable"				δ_T	δ_e	
69		5	5	3		δ_e	δ_T	
69		8				δ_T	δ_e	
70		4	4	3	3	δ_e	δ_T	
70		8				δ_T	δ_e	
71		5	5	4		δ_e	δ_T	
71		6				δ_T	δ_e	
68		6	6	5		δ_e	δ_T	
71		5	5	4		δ_e	δ_T	
72		5	5.5	4.5		δ_e	δ_T	
57	J	4	3.5	3	4	δ_e	δ_T	Basic, C_{l_p} = −1.72, $C_{l_{\delta_a}}$ = 0.32
57	J	4.5	4		5	DDC†	δ_T	
57		4.5	4		5	δ_e	δ_T	No requirement for DDC
57		4.5	4		5			" " " "
57		4.5	4		5			" " " "
62		4.5	4		5			" " " "
62		4.5	4		5			" " " "
62		4.5	4		4			" " " "
57		4.5	4		4			" " " "
65		4.5	4		2.5	δ_e, DDC		
65		4.5	4		3			
65		6	6	6	6	DDC		
57		4	4		4	δ_e		No requirement for DDC
72		4	4		4			" " " "
73		10				δ_e, δ_T		
74		10						
57		4	4	4		δ_e		
57		4.5	4.5	4	4			
57		4.5	4.5					
57		4	4	4	5			
57		4	4	4	4			
57		4	4	4	4			
80		9	8.5	8.5	9			
81			8 IFR 9 VFR	7				
82		7.5	7.5	7.5	7.5			
83		6	6	6	5			
57		5	5	5				
57		4						
58		5.5/5.5*	5/5	6/6	5/5	δ_e/DDC*		
59		7.5/6	7.5/6	7.5/6	-/3			
60		5/5	4/4	4.5/4.5	3/3			
61		3.5/3.5	3.5/3.5	3.5/3.5	4/4			
63		4.5	4.5	4.5		δ_e		
64		10/7	10/7	10/7		δ_e, δ_T/DDC		
57		7.5/4	7.5/4	-/4	6/4	δ_e/DDC		
57	F	8	5		8	δ_T	δ_e	
58		8/8.5*	8/8.5			δ_e/DDC*	δ_T/δ_e	
75		6				δ_T	δ_e	

*Slash marks indicate split ratings or control techniques used without DDC and with DDC, respectively; i.e., without/with DDC.

†DDC indicates use of direct drag control by pilot (see Appendix A).

TABLE A-7 (Concluded)

CONFIG. NO.	PILOT	PILOT RATINGS				PRIMARY CONTROL		MISCELLANEOUS
		OVERALL	GLIDE PATH	SPEED	FLARE	SPEED	GLIDE PATH	
72	K	6	4	5		δ_T	δ_e	
73		10	9.5	9	10	δ_e	δ_T	
73		6	5	6		δ_T	δ_e	
74		7	7	8		δ_e	δ_T	
74		4	4	4		δ_T	δ_e	
75		8	8	8		δ_T	δ_e	
75		7	7	7	4	δ_e	δ_T	SAS inoperative
76		10				δ_T	δ_e	SAS inoperative
76		6	6	6		δ_e	δ_T	SAS inoperative
75		9				δ_T	δ_e	
75		6	6	4	6	δ_e	δ_T	
76		10				δ_T	δ_e	
76		5	5	4	5	δ_e	δ_T	
77		8	8	10		δ_T	δ_e	
77		4.5	4.5	4	4	δ_e	δ_T	
66	A	6	6	3	7	δ_e	δ_T	
66		10				δ_T	δ_e	
67		6.5				δ_e	δ_T	
67		10				δ_T	δ_e	
68		8.5	8	8	9	δ_e	δ_T	
68		10				δ_T	δ_e	
69		8				δ_e	δ_T	
70		4.5	4.5	4		δ_e	δ_T	
70		6.5	6.5	6.5		δ_T	δ_e	
71		5	4	4	6.5	δ_e	δ_T	
71		7				δ_T	δ_e	
72		10				δ_e	δ_T	
73		7	6	7	7	δ_e	δ_T	
73		"Ridiculous"				δ_T	δ_e	
73		5.5	5	6	4	δ_T	δ_e	
73		5	4	6	4.5	δ_e	δ_T	
74		4.5	4	5	4.5	δ_e	δ_T	
74		5	4.5	6	5	δ_T	δ_e	
75		10	7	10		δ_T	δ_e	
75		8	7	9	8	δ_e	δ_T	
76		10	9	10	10	δ_T	δ_e	
76		6	5	6	5	δ_e	δ_T	
77		10	10	10		δ_T	δ_e	
77		6	6	6		δ_e	δ_T	
78		10				δ_T	δ_e	
78		6.5	6	7	6	δ_e	δ_T	
79		10				δ_T	δ_e	
79		5	5	5	5	δ_e	δ_T	
80		10	10	10	7	δ_T	δ_e	

CONFIG. NO.	PILOT	PILOT RATINGS				PRIMARY CONTROL		MISCELLANEOUS
		OVERALL	GLIDE PATH	SPEED	FLARE	SPEED	GLIDE PATH	
80	A	5	5	5		δ_e	δ_T	
81		10	7	9.5		δ_T	δ_e	
81		6	6	6		δ_e	δ_T	
82		10	9	10	10	δ_T	δ_e	
82		5	4	6		δ_e	δ_T	
83		5	4	5	.5	δ_T	δ_e	
83		9	9	9		δ_e	δ_T	
77	K	5	5	4	4	δ_e	δ_T	
78		5	5	5	6	δ_T	δ_e	
78		4	4	4	4	δ_e	δ_T	
79		10	10	10	10	δ_T	δ_e	
79		5	5	4		δ_e	δ_T	
80		10				δ_T	δ_e	
80		5	5	5	4	δ_e	δ_T	
81		9.5	9.5	9.5		δ_T	δ_e	
81		10	10	10		δ_e	δ_T	
82		4	4	2		None	δ_e	
82		9	9	9		δ_e	δ_T	
83		6				δ_T	δ_e	
83		6.5	6	5	6.5	δ_e	δ_T	
75		6.5			6	δ_e	δ_T	
78		5.5			5	δ_e	δ_T	
78		"Couldn't correct back"				δ_T	δ_e	
79		5				δ_e	δ_T	
79		"Couldn't correct back"				δ_T	δ_e	
80		5			5.5	δ_e	δ_T	
80		"Couldn't correct back"				δ_T	δ_e	
81		5			5	δ_e	δ_T	
81		"Couldn't correct back"				δ_T	δ_e	
82		"Couldn't correct back"				δ_e	δ_T	
82		5			5	None	δ_e	
83		"Couldn't correct back"				δ_e	δ_T	
83		5			5	None	δ_e	

Equations of Motion

General nonlinear flight path translation equations of motion and body-axis angular acceleration equations were used for the simulation.

Flight Path Translational Equations of Motion

$$-C_D(\alpha^*, T_c, \delta_F)\bar{q}S + \Delta D_V(V^* - V_o) + C_{D_{\delta_t}}\delta_t\,\bar{q}S$$

$$+ \Delta C_{D_\alpha}(\alpha^* - \alpha_o)\bar{q}S + \Delta C_{D_{T_c}}(T_c - T_{c_o})\bar{q}S + C_{D_{\delta_3}}\delta_3\,qS - mg\sin\theta = m\dot{u} + qw - rv$$

$$C_{y_p}\frac{b}{2V^*}p^* + C_{y_r}\frac{b}{2V^*}r^* + C_{y_{\dot\beta}}\frac{b}{2V^*}\dot\beta + C_{y_\beta}\beta^*$$

$$+ C_{y_{\delta_r}}\delta_r\,\bar{q}S + mg\cos\theta\sin\varphi = m(\dot{v} + ru - pw)$$

$$-\left[C_L(\alpha^*, T_c, \delta_F) + C_{L_q}\frac{\bar{c}}{2V^*}q^* + C_{L_{\dot\alpha}}\frac{\bar{c}}{2V^*}\dot\alpha + C_{L_{\delta_e}}\delta_e\right]\bar{q}S$$

$$+ \left[\Delta C_{L_{T_c}}(T_c - T_{c_o}) + C_{L_{\delta_2}}\delta_2 + \Delta C_{L_\alpha}(\alpha^* - \alpha_o)\right]\bar{q}S$$

$$+ \Delta L_V(V^* - V_o) + mg\cos\theta\cos\varphi = m(\dot{w} - pv - qu)$$

Body-Axis Rotational Equations of Motion

$$\left(C_{\ell_\beta}\beta^* + C_{\ell_p}\frac{b}{2V^*}p^* + C_{\ell_r}\frac{b}{2V^*}r + C_{\ell_{\delta_a}}\delta_a + C_{\ell_{\delta_r}}\delta_r\right)\bar{q}Sb$$

$$= \dot{p}I_x - \dot{r}I_{xz} + qr(I_z - I_y) - pqI_{xz}$$

$$\left(C_{n_\beta}\beta^* + C_{n_{\dot\beta}}\frac{b}{2V^*}\dot\beta + C_{n_r}\frac{b}{2V^*}r^* + C_{n_p}\frac{b}{2V^*}p^* + C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r\right)\bar{q}Sb$$

$$= \dot{r}I_z - \dot{p}I_{xz} + pq(I_y - I_x) + qrI_{xz}$$

$$\left(C'_{m_\alpha}\alpha^* + C_{m_q}\frac{c}{2V^*}q^* + C_{m_{\dot\alpha}}\frac{c}{2V^*}\dot\alpha + C_{m_{\delta_e}}\delta_e + C'_{m_{\alpha=0}}\right)\bar{q}Sc$$

$$= \dot{q}I_y + pr(I_z - I_x) + (p^2 - r^2)I_{xz}$$

where

$$p^* = p - p_g$$

$$q^* = q - q_g$$

$$r^* = r - r_g$$

$$\alpha^* = \tan^{-1}\left[\frac{w - w_g}{u - u_g}\right]$$

$$\beta^* = \tan^{-1}\left\{\frac{v - v_g}{\left[(u - v_g)^2 + (w - w_g)^2\right]^{1/2}}\right\}$$

$$V^{*2} = (u - u_g)^2 + (v - v_g)^2 + (w - w_g)^2$$

$$\bar{q} = \frac{1}{2}\rho V^{*2}$$

$$C'_{m_\alpha} = C_{m_\alpha} + \Delta(C_{m_\alpha})_{G.E.}$$

$$C'_{m_{\alpha=0}} = C_{m_{\alpha=0}} + \Delta(C_{m_{\alpha=0}})_{G.E.}$$

where $\Delta(C_{m_\alpha})_{G.E.}$ and $\Delta(C_{m_{\alpha=0}})_{G.E.}$ are defined by Fig. A-1

The variation of thrust with speed was simulated by the following expression:

$$T = \frac{550(0.43 + 0.0021\, V^*)}{V^*} \times HP$$

Simulated Atmospheric Turbulence

The random turbulence model used during the simulator program is based on the Dryden form of the spectra (Refs. 9 and 15).

The spectra for the turbulence velocities:

$$\varphi_{u_g}(\omega) = \frac{\sigma_u^2\, 2L_u}{\pi\, \bar{V}_o}\; \frac{1}{1 + (L_u\, \omega/\bar{V}_o)^2}$$

$$\varphi_{v_g}(\omega) = \frac{\sigma_v^2 L_v}{\pi \overline{V}_o} \frac{1 + 3(L_v \omega/\overline{V}_o)^2}{\left[1 + (L_v \omega/\overline{V}_o)^2\right]^2}$$

$$\varphi_{w_g}(\omega) = \frac{\sigma_w^2 L_w}{\pi \overline{V}_o} \frac{1 + 3(L_w \omega/V_o)^2}{\left[1 + (L_w \omega/\overline{V}_o)^2\right]^2}$$

$$\varphi_{p_g}(\omega) = \frac{\sigma_w^2}{L_w \overline{V}_o} \frac{0.8(\pi L_w/4b)^{1/3}}{1 + (4b\, \omega/\pi\overline{V}_o)^2}$$

$$\varphi_{q_g}(\omega) = \frac{(\omega/\overline{V}_o)^2}{1 + (4b\omega/\pi\overline{V}_o)^2} \varphi_{w_g}(\omega)$$

$$\varphi_{r_g}(\omega) = \frac{(\omega/V_o)^2}{1 + (3b\omega/\pi\overline{V}_o)} \varphi_{v_g}(\omega)$$

where

$$L_u = L_v = L_w = 1750 \text{ ft}, \quad h \geq 1750 \text{ ft}$$

$$\left.\begin{aligned} L_w &= h \\ L_u &= L_v = 145(h)^{1/3} \end{aligned}\right\} \quad h < 1750 \text{ ft}$$

$\overline{V}_o$ = Initial total velocity (ft/sec)

ω = Frequency (rad/sec)

σ = Standard deviation (ft/sec)

It was desired to use a light to moderate turbulence level for the investigation. This has qualitatively been found (Ref. 2) to be approximated by $\sigma_w = 3$ ft/sec based on an average altitude of 500 ft and where the other gust intensities are proportional:

$$\frac{\sigma_u^2}{L_u} = \frac{\sigma_v^2}{L_v} = \frac{\sigma_w^2}{L_w}$$

Pitch Stability Augmentation System

A pitch rate command, attitude hold stability augmentation system (SAS) was used in the simulation. A block diagram of the system is presented as Fig. A-1. The pitch and pitch rate feedbacks provide attitude stiffness and damping to suppress disturbances. The pitch SAS frees the pilot of the task of attitude stabilization of disturbances and allows for a more direct study of the tasks of flight path control and/or speed control through elevator.

Direct Drag Control

A direct drag control (DDC` was available as an alternate speed control devide in some of the initial test runs. This control was manually operable by the pilot from a thumb switch located on the throttle lever. This switch provided an "on-off" rate command control of a drag increment of approximately 0.2g acting along the body axis in a manner analogous to conventional direct lift control (DLC). Unfortunately, this additional control tended to complicate the piloting task and its use was discontinued after only a short evaluation.

Control Sensitivity — Rate Command

The control sensitivity for the rate command was initially set to give 3 deg/sec/in. of column; however, each pilot was given the opportunity to tune the response and sensitivity to his taste. This tuning took place during the familiarization period and no data was recorded as to the optimums selected although in general the changes relative to the base value were small, falling somewhere between 2.5 deg/sec/in. and 5 deg/sec/in.

Outline of Pilot Briefing

The object of this simulation is to examine flight path and speed control factors for STOL aircraft.

In order to focus on speed and flight path controllability the task of attitude control is minimized by a rate command/attitude hold SAS in the pitch axis. The pilot therefore has the following controls available:

- Commanded attitude, θ_C
- Commanded throttle, δ_T

In some cases the pilot has a direct drag control also available (δ_D).

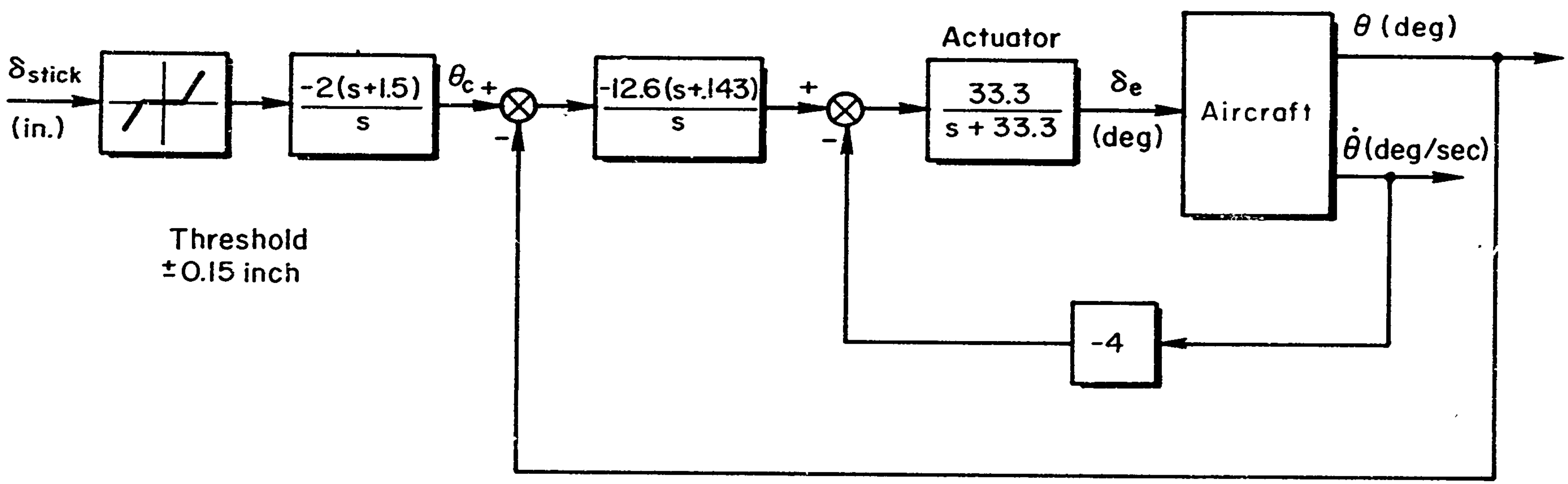

Figure A-1. Pitch Attitude Augmentation Scheme
(Rate Command-Attitude Hold)

The variables of the simulation are:

- X-force due to angle of attack change
- Angle of thrust resultant
- Presence of a pure drag control

For each configuration the pilot will be asked to consider a specific control technique, one of which is probably more effective (e.g., if the thrust vector is near vertical the pilot will be told to try controlling speed with θ_C or δ_D and flight path with δ_T). However, this information is only meant as a rough guide; the pilot is free to use either technique or combination that he feels is appropriate.

The task consists of a straight-in ILS approach including beam acquisition, beam tracking, and flare. Separate pilot ratings are to be given for:

- Glide slope tracking task
- Speed control
- Flare

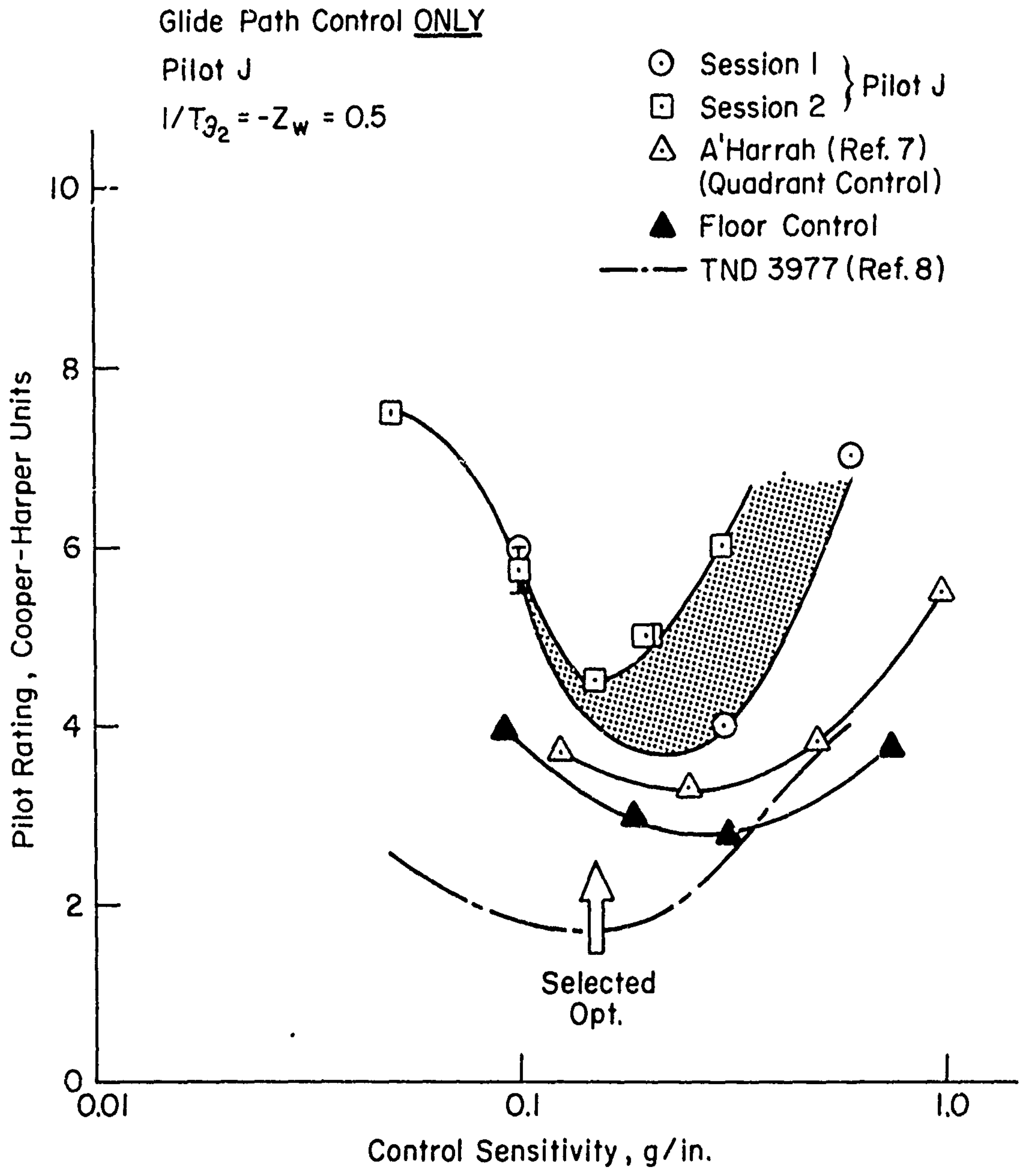

Figure B-1. Thrust Control Sensitivity Effects on Pilot Rating

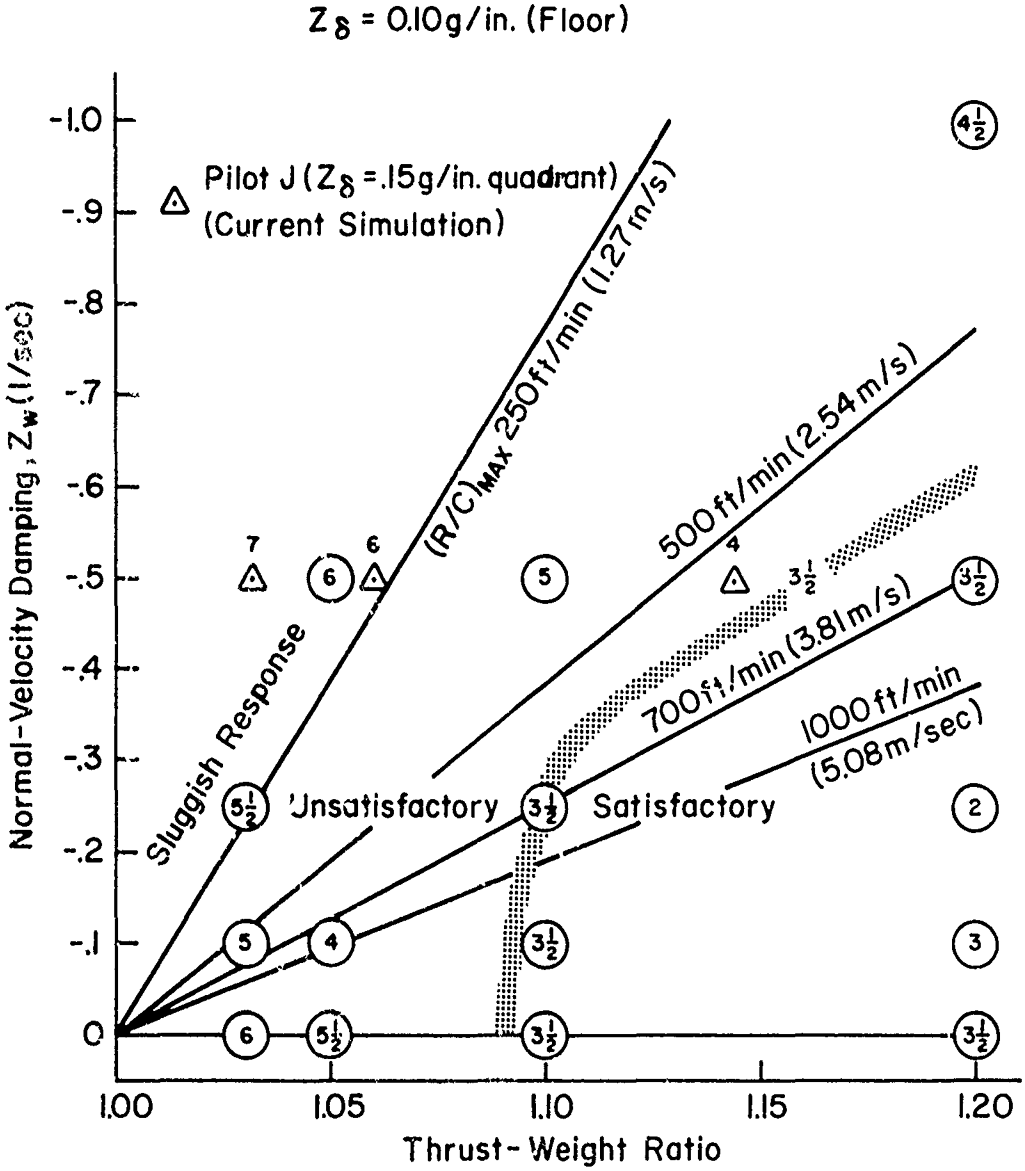

Figure B-2. IFR Approach and Landing Task Control Power Requirements for Steep Approach; γ = 7.5 Deg (Ref. 8)

TABLE B-1

RESULTS OF THROTTLE CONTROL STUDY

(Ref. 1)

ESTABLISHMENT OF THROTTLE SENSITIVITY AND AUTHORITY								
CONFIG. NO.	PILOT	PILOT RATINGS				n_{δ_T} (g/in.)	$C_{L_{\delta_T}}$ (1/in.)	MISCELLANEOUS
		OVERALL	GLIDE PATH	SPEED	FLARE			
52	J	7	4			0.3	1.47	Lateral control problems restricted overall rating.
		7	6	4		0.1	0.49	
		6.5	7			0.6	2.94	
		6	5			0.2	0.98	
		6.5	7.5		4	0.05	0.25	
		6	6		5	0.3	1.47	
		6	5			0.2	0.98	
		6	4.5	4	5	0.15	0.73	
		7	6		6	0.1	0.49	
54		6	4		3	0.15	0.73	$n(\delta_T)_{max}$ = 0.084g
55		5.5	4					= 0.132g
56		6	6					= 0.066g
56			6.5					= 0.033g